Lake Spokane
Measuring Improvement
in Dissolved Oxygen
and Ecosystem Health

A Literature Review

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A Literature Review

by

Paul J. Pickett

Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington 98504-7710

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Abstract

Lake Spokane is the focus of a restoration effort to improve dissolved oxygen (DO) in the lake by reducing phosphorus loading in the Spokane River. A literature review was conducted to identify and evaluate alternative methods or analyses that could be used to measure improvements in water quality, reservoir health, and support for aquatic life in Lake Spokane. The review focused on DO levels in reservoirs and on ecosystem processes related to DO, and evaluated academic research and applied science used in systems similar to Lake Spokane.

Over 130 articles and books were reviewed and included in the search. Information was categorized into topics related to reservoir ecosystem: dissolved oxygen dynamics; trophic state; primary production; sediment (oxygen demand, nutrient diagenesis, and paleolimnology); phytoplankton (algal assemblages and chlorophyll-*a*); and fish ecology (fish volitional movement, bioenergetics, and the temperature-DO squeeze). Information was also presented regarding: climate, hydrology, and flow; structural and operational factors; and indicators, criteria, and multi-parameter assessments. The methods were analyzed for their ability to assess change over time, and prioritized within categories of: statistical methods (trends and comparison of two time periods); modeling methods; and graphical methods.

The report makes prioritized recommendations for future data collection and analysis, which are organized into: analyses with existing data; supplementation of ongoing monitoring; recovery assessment studies; studies of ecosystem functions; modeling support and enhancement; and overarching support and strategy.

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Introduction

Problem description

The Spokane River and Lake Spokane dissolved oxygen total maximum daily load (DO TMDL), approved in 2010, used the CE-QUAL-W2 ("W2") model to evaluate DO in the river and reservoir under a variety of conditions. The Department of Ecology (Ecology) found that conditions in the riverine and lacustrine portions of Lake Spokane (the reservoir created by Long Lake Dam) did not meet the water quality standards for DO, with the segment in front of Long Lake Dam having the most impairment. The source of the impairment was found to be nutrients from point and nonpoint sources.

By 2020, a variety of point and nonpoint implementation actions will occur. Ecology anticipates conducting a 10-year assessment of the Spokane River and Lake Spokane to determine progress toward meeting the DO TMDL allocations beginning no earlier than 2021. Stakeholders have expressed interest in exploring alternatives in addition to the CE-QUAL-W2 model to assess the progress of implementing the DO TMDL. Therefore, Ecology's Water Quality Program, Eastern Regional Office requested that Ecology's Environmental Assessment Program conduct a literature review.

Study purpose

The purpose of the literature review was to identify and evaluate alternative methods or analyses that could be used to measure improvements in water quality, reservoir health, and support for aquatic life in Lake Spokane (Figure 1). The review focused on DO levels in lakes and on lake ecosystem processes related to DO, including both internal processes and external influences. The search evaluated academic research and applied science used in systems similar to Lake Spokane and the Spokane River.

Determining compliance with water quality standards is the core purpose of the DO TMDL, and is the responsibility of Ecology's Water Quality Program. Evaluating these methods for demonstrating compliance with water quality standards was beyond the scope of this project.

Figure 1. Long Lake, with baseline monitoring stations.

Inset map: location of Spokane river watershed. HED = Hydroelectric Dam. (From: Avista (2017.)

Study objectives

- Identify and summarize scientific literature which documents ways to assess reservoir water quality and aquatic habitat health, focusing on processes related to the DO impairments addressed by the DO TMDL.

- Analyze and evaluate the identified literature in terms of:
  o The technical applicability of methods as indicators for DO TMDL implementation targets and for related factors such as trophic status and ecological structure.
  o The ability of methods to characterize trends and rates of recovery.

- The policy and regulatory context of the method, its endpoint or success measures, and how these are similar to, or different than, the DO TMDL.

- Identify and recommend feasible and useful methods that can inform the DO TMDL 10-year assessment.

Approach

This review was conducted through textbooks; generic internet search; search engines for journals, government agencies, and academic libraries; cited references; and personal contact with researchers. Search parameters for "reservoir" and "dissolved oxygen" were the most productive. Search results were filtered for deep stratified lakes in a temperate climate. First priority were studies in the Pacific Northwest, followed by studies across North America and relevant academic studies. A few relevant studies from Europe were found. Studies were included that addressed modeling, monitoring, or combinations of both.

For the most part, studies were screened out that were related to:

- Shallow, unstratified reservoirs
- Natural lakes with studies not relevant to reservoirs
- Reservoirs in non-temperate climates, such as subarctic or tropical reservoirs
- Studies about lake treatment methods, unless the study included pre-treatment reservoir assessment.

Many studies of Lake Spokane were conducted in the 1980s and 1990s. These were not included in the review because they were conducted before the TMDL was completed, and because the scope of this study was for "alternative" methods. However, this is a useful body of work which can be evaluated as a foundation for future study.

Results

Literature sources

Over 120 references were identified as relevant to this study and reviewed. These included:
- 13 textbooks or conference proceedings
- 76 from academic journals
- 36 from government agencies
- 2 Masters theses

Many others were screened and rejected.

The context of the studies varied widely. General categories include:
- TMDL-related studies
- Project impact studies
- Lake assessments
- Fisheries studies and research
- Academic research
- Policy documents for science guidance

DO in the aquatic ecosystem

In interpreting the results of this study, it's important to understand the interaction of dissolved oxygen with the aquatic ecosystem of the reservoir. Figure 2 illustrates these relationships. These general principles are found in a variety of limnology textbooks and compilations (see Table A-1 in Appendix A).

A key physical feature that temperate zone deep lakes and deep reservoirs like Lake Spokane have in common is density stratification during the summer. This is commonly caused by thermal stratification, although salinity can also affect stratification in some cases. The well-mixed warmer surface waters are termed the *epilimnion*, the deep poorly-mixed colder waters are termed the *hypolimnion*, while the layer of rapid temperature transition between the epilimnion and hypolimnion is termed the *metalimnion*.

Another key feature common to deep reservoirs is the designation of longitudinal zones as *riverine*, *transition*, and *lacustrine*. These features in Lake Spokane are shown in Figure 1. The riverine zone is shallow and usually well-mixed, but with decreasing velocities and increasing deposition of suspended materials. The lacustrine zone is the deepest are and exhibits the full characteristics of a stratified lake. The transition zone is shallower than the lacustrine zone, but experiences more stratification than the riverine zone.

In a reservoir, the mass balance of DO is affected by tributary inflows and downstream flow releases. Critical hydraulic features in a reservoir include the number, location, and flow volume of tributaries, and the elevation and flow volume of outlet flow. The net difference of inflows

and outflows results in the filling or draining of the reservoir. In a reservoir, the outlet depth and extent of draw-down can have a significant effect on the vertical density, chemical, and biological structure of the waterbody.

Several features unique to reservoirs can be found in Lake Spokane. The outlet depth drives the hydraulics of the reservoir by creating an "interflow" zone between the epilimnion and hypolimnion. The interflow, in combination with the temperature of the inflowing river creates a "plunging" of inflows from the riverine section of the reservoir into the interflow zone. Adding to this complexity are operational choices related to the balancing of power generation needs with stable lake levels for summer generation.

Oxygen can exchange between the dissolved phase in the reservoir and the gaseous phase in the atmosphere, either by reaeration or degassing. This exchange, as described by Henry's law, seeks equilibrium between DO percent saturation of the surface water and the partial pressure of oxygen in the atmosphere. Diffusion rates in calm water and still air are low and can limit DO exchange. However, water turbulence caused by currents or wind shear can produce much higher exchange rates.

Within the reservoir, DO can be increased by gross primary productivity (GPP). GPP describes the process where plants and algae use photosynthesis to take up nutrients and carbon dioxide and produce organic carbon, also producing DO as a byproduct. The source of GPP can be pelagic (phytoplankton) or littoral (periphyton and macrophytes in the shallower shore areas).

Phytoplankton GPP occurs in the *photic zone*, the depths where sunlight is sufficient for photosynthesis. The photic zone extends roughly from the surface to the depth where light is reduced to 1% of surface values. This typically includes most or all of the epilimnion and often most of the metalimnion. The depths where GPP occurs is termed the *trophogenic zone*.

In a relatively clear lake the photic zone and trophogenic zone may coincide, and maximum phytoplankton levels may be well below the surface, sometimes in the metalimnion or the interflow zone of a reservoir. However, in a nutrient-enriched lake with high phytoplankton biomass, self-shading may limit the highest GPP rates and algal levels to relatively shallow surface waters (Wetzel, 2001).

DO levels in the water column and at the sediment interface can be lowered by respiration and oxidation. Photosynthetic plants and algae are producing oxygen during daylight. Vegetation, algae, and other living organisms respire in the water column, littoral zones, and sediment surface layers, taking up DO throughout the day and night at rates proportionate to their biomass, metabolism, ambient temperatures, and other factors. Net GPP in the day increases DO, but at night only respiration is occurring. This creates a diel swing of DO between high daytime and low nighttime levels of saturation, which is a key feature of a productive reservoir.

DO can also be removed from the water column by chemical oxidation. At the sediment interface, DO can be taken up in the sediment by forms of carbon, iron, manganese, sulfur and other compounds – a process known as sediment oxygen demand (SOD). In the overlying water, dissolved carbon and other reduced compounds can also remove DO by oxidation. This process

is commonly termed biochemical oxygen demand (BOD), which is categorized into carbonaceous BOD (CBOD – the oxidation of methane and organic carbon) and nitrogenous BOD (NBOD – the oxidation of ammonia and organic nitrogen).

Oxygen in the water column will tend to diffuse along gradients from high to low levels, but the rate of transfer by diffusion is relatively slow. Therefore, when stratification isolates the hypolimnion, DO levels commonly will drop, becoming *hypoxic* (oxygen depleted below saturation) or *anoxic* (little or no oxygen). With stable density stratification these conditions may last for months. In autumn, as surface temperatures cool the density gradient created during the summer weakens. Typically the first strong storm in autumn will trigger "fall turnover", or complete mixing of the lake or reservoir.

Lakes in northern latitudes will often experience winter stratification, when bottom waters are 4 ºC (the maximum density of liquid water) and surface waters are frozen or near freezing. In these situations a spring overturn may also trigger an algal bloom. However, this is unlikely to occur in Lake Spokane, given the high levels of spring runoff and reservoir operations. The focus of this study will be on summer and fall conditions.

Because of these complex interactions, dissolved oxygen conditions are intimately linked with the biota of the aquatic ecosystem and with the transport and transformation of nutrients and organic material. These relationships will be explored further as results of the literature review are discussed.

Categories of approaches

Reservoir limnology is a vast and highly studied topic. To help with organizing material, several categories of assessment methods are employed:

- Dissolved oxygen dynamics
- Trophic state
- Primary production analysis
- Sediment assessment
- Phytoplankton assemblages
- Fish ecology
- Weather, hydrology, and flow
- Climate change impacts
- Indicators, criteria and multiparameter assessments

The effects of reservoir structure and operations are unique factors in understanding reservoir limnology, and methods to analyze these factors are presented.

A key objective of the study is to evaluate methods to assess trends and recovery rates for Lake Spokane. This particular question can be addressed by many different assessment methods, and is therefore discussed specifically in more detail after the assessment methods are presented.

Figure 2. Conceptual model of the biological and physical components contributing to variability in dissolved oxygen in a lake. (Modified from Staehr, 2010).

Green arrows are processes that tend to increase oxygen levels, while gray arrows represent processes that decrease oxygen levels. Arrows of other colors represent processes that transport oxygen into, out of, and within the lake.

Summary table of results

A table that summarizes the result of this literature review is provided in Appendix A. Summary table of methods reviewed, Table A-1. This table provides the following information:

- **Method:** The name of the type of method
- **Category:** The category the method falls in, corresponding to sections in this report. The hyperlinked page number of the section is included.
- **Purpose:** The primary purpose of the method
- **Contexts:** The contexts in which the method was used as reported in the literature
- **Recovery Assessment:** How the method might be used in a recovery assessment
- **Case Study Locations:** The locations of case studies using the method, classified as: Europe; Canadian province; USA – nationwide, region, or state; or western or eastern Washington
- **Useful to Lake Spokane:** A prioritization and brief summary of the usefulness of the method for assessing Lake Spokane as part of the TMDL 10-year assessment. The basis of the priorities:
  - *High:* well established method, fills a critical gap, supports trend or recovery analysis
  - *Medium:* useful tools – either simple to do but of secondary value; or high value but logistically complex
  - *Low:* useful, but of limited value
- **Citations:** The relevant citations, as numbered in the References section.

Dissolved oxygen dynamics

A variety of methods have been developed and applied that directly evaluate DO conditions in a reservoir as a metric of reservoir health. DO metrics can provide information on the sensitivity of the reservoir to oxygen-demanding processes, the comparative health of reservoirs, the variability of conditions over space and time, and the relative severity of restrictions on fish habitat.

Hypoxia/anoxia analysis

Water column DO demand

A key component of metabolism and oxygen balance in a reservoir is the oxygen demand in the water column. This needs to be known in order to separate it from the effects of algal respiration and sediment oxygen demand. For that reason, water quality modeling requires good estimates of CBOD and NBOD.

Two references from the Klamath River TMDL studies explored this parameter specifically. Doyle and Lynch (2005) conducted SOD measurements in the laboratory, and estimated water column DO depletion from the overlying water used in the control chamber. They note that although their method "is not equivalent to a standard biological oxygen demand (BOD) measurement, it does provide information as to the potential oxygen demand in the water column

without photosynthesis. It also provides insights as to the relative importance of oxygen demand in the water column versus the bottom sediments…"

Flint, et al. (2004) reviewed modeling of the Klamath River, which included CE-QUAL-W2 (W2) simulations. The methods reported in Doyle and Lynch (2005) were discussed, and the importance of water column BOD was emphasized. BOD was identified as a critical component of DO depletion in this system, and was highlighted as a data gap.

Hypoxic/anoxic factor

The Hypoxic Factor (HF) and Anoxic Factor (AF) were developed by Gertrud Nürnberg and reported in several journal articles (Nürnberg, 1995; 1996; 2002; 2004). The AF is expressed in units of time and is defined as:

$$AF = \sum_{i=1}^{n} \frac{t_i \, a_i}{A_0}$$

where:
- n = number of periods with different oxycline depths
- t_i = the period of anoxia (days)
- a_i = the area of the upper boundary of the anoxic layer
- A_0 = the lake surface area corresponding to the average elevation for that period.

Nürnberg (1996) studied data sets for lakes in North America, Europe, and Asia, and found strong relationships between the AF and trophic state:
- Below 20 days/year indicate oligotrophic conditions.
- 20-40 days/year suggest a mesotrophic lake.
- 40-60 days/year represents eutrophic conditions.
- Above 60 days/year is typical for hypereutrophic conditions.

The HF is similar to the AF, except instead of a threshold for anoxic conditions, such as <1 mg/L DO, a specific higher threshold is selected, such as a DO level of 6.5 mg/L. The areas at that HF threshold depth for each period are entered into the same equation.

Nürnberg (2002) evaluated 12 years of DO data from Brownlee Reservoir on the Snake River (on the Oregon-Idaho border). An AF based on 2 mg/L and an HF based on 6.5 mg/L was evaluated for the whole reservoir and in the lacustrine areas for the whole water column and for the epilimnion. AF values ranged from 8 to over 100 days, while HF values ranged from 34 to over 200 days.

Nürnberg (2004) extended the analysis to explore variability in the method. The accuracy of the AF can be improved by using profiles from more periods during the year. Better AF values are also obtained by calculating AF in multiple reaches or sections of the lake or reservoir with different morphologies, such the riverine and lacustrine areas, or multiple basins or arms. The AF was found to be "more robust and exact" than other methods, and correlated well with trophic states and internal P loading. The HF (or AF) can be used as a way to assess compliance with a water quality criterion. Both methods allow trends in conditions to be assessed.

Other examples of studies that used the AF for assessing reservoir conditions include:
- Beutel (2003), who evaluated conditions in drinking water reservoirs in California.
- Kesler and Verschuur (1996) who studied a reservoir in Tennessee.
- Marcé et al. (2010) who evaluated the effect of climate impacts on reservoirs in Spain.

Hypolimnetic oxygen depletion

Hypolimnetic Oxygen Depletion (HOD) has been used as a measure of lake or reservoir health in many studies. It was first explored over a century ago and developed in its current form in the 1930s (Wetzel, 2001). Described simply, HOD is the slope of the line for the mass of oxygen in the hypolimnion versus time from spring turn-over (fully mixed, fully oxygenated conditions), until anoxia or the end of the linear decline.

To standardize HOD by lake, the Areal HOD (AHOD) is commonly used. For AHOD, the change in the mass of oxygen in the hypolimnion is calculated and divided by the surface area of the hypolimnion, resulting in a value of mg-DO cm^{-2} day^{-1}. A volumetric HOD (VHOD) is also used, based on the HOD divided by the volume of the hypolimnion.

Citations found in the literature search that describe or use HOD methods are listed in Table 1. The method has been applied across North America for lake assessments, recovery assessments, project impact analysis, and protection of drinking water.

Table 1. References for HOD methods.

Beutel, 2003	Chapra, 1997	Cooke et al., 2011
Cornett and Rigler, 1980	De Lanois and Green, 2011	Hudson and Vandergucht, 2015
Kesler and Verschuur, 1996	Lehman, 1988	Matthews and Effler, 2006
Miller, 2010	Nürnberg, 1996	Nürnberg, 2004
Welch et al., 2015	Wetzel, 2001	Wetzel and Likens, 2000

Studies have noted limitations to this method.
- Cornett and Rigler (1980) concluded that the ability to compare AHOD between lakes was limited, due to the complexity of lake morphology and temperature regimes. Processes that complicate interpretation of AHOD include: vertical mixing and diffusion rates; organic material inflow rates; the thickness and temperature of the hypolimnion; photosynthesis rates; and differences between water column and sediment oxygen demand. Beutel (2003) in particular noted this last effect. Wetzel (2001) notes that the method works best when little or no anoxia is occurring in the waterbody.
- Matthews and Effler (2006), Miller (2010), and others have noted that the AHOD may be insensitive to recovery because of the slow response of sediment diagenesis and oxygen demand.
- Welch et al. (2015) found that, after a decrease of almost 80% from the 1970s to 2000, oxygen depletion rates in Lake Spokane have remained "consistently low for nearly the past decade and a half." The researchers note that in recent years, with lower TP levels, a larger fraction of TP loading may be internal and interannual variations in climate and flow may have a stronger effect on minimum DO levels.
- As noted above, Nürnberg (2004) felt that AF and HF method to be superior to HOD.

Several studies used adjustments to AHOD to account for complicating factors, including De Lanois and Green (2011) who used a "flushing rate" adjustment, and Matthews and Effler (2006) who used two factors: "(1) vertical mixing inputs of DO from overlying layers into the hypolimnion and (2) temperature of the hypolimnion."

As Lanois and Green noted, reservoir flushing rates have an impact on AHOD estimates, and Nürnberg (2004) observed that hydrology drives interannual variability. Miller (2010) noted the impact of drawdown on HOD estimates, while Hudson and Vandergucht (2015) noted that drought and low flow caused worsening VHOD conditions.

Several references report that AHOD correlates to trophic status metrics, including Nürnberg (1996) who cites correlations to total phosphorus (TP) concentrations, and Chapra (1997) who cites correlations to chlorophyll-*a*. Kesler and Verschuur (1996) cite studies that correlate AHOD to TP and Secchi depth.

Several studies report success in assessing recovery with AHOD, including:

- De Lanois and Green (2011), who used multivariate regressions to detect improvements in AHOD
- Matthews and Effler (2006), who found a decrease in AHOD levels when comparing two time periods.
- Lehman (1988), who reported that "reduction of the nutrient income to Lake Washington … led to reduced rates of oxygen depletion in the hypolimnion…" However he also notes that "areal oxygen consumption can be relatively insensitive to volumetric changes in plankton abundance."

Areal hypolimnetic mineralization

One study (Müller et al., 2012) explored a method that the authors called "Areal Hypolimnetic Mineralization" (AHM). This method calculates the mineralization of carbon and other reduced compounds, both in the water column and at the sediment-water interface from diffusion up through the sediment. AHM is calculated from water column and sediment core chemistry. The researchers found a strong relationship to hypolimnetic thickness, and noted that AHM values tended to be higher than AHOD because of the inclusion of reduced compounds. The article concludes that "this model has important implications for predicting and interpreting the response of lakes and reservoirs to restoration measures."

DO temporal or seasonal analysis

A variety of methods were found in studies that analyzed DO levels over time, which can include seasonal change within a year or inter-annual changes over many years. There is a lot of overlap between temporal and spatial analysis, since many use combinations of both. But to organize information, methods are first presented that are primarily focused on DO patterns over time.

The time below a threshold and percentiles over time have been applied to TMDL analyses. Examples include:

- Miller (2010) reported on W2 modeling for Utah's East Canyon Reservoir TMDL. For comparing TMDL scenarios he calculated the number of days per year when the water quality criteria were violated.

- Tetra Tech (2009b) evaluated TMDL compliance in the Klamath River by comparing model scenarios between a natural conditions baseline scenario and a TMDL compliance scenario, based on the calibration year of 2000 (a year of flows close to the long-term average). The natural conditions scenario adjusted flows (natural flows from major tributaries, and removal of point sources and "accretions") and pollutant loading. The deficits between the natural and compliance scenario results were calculated, and then compliance was assessed as the percent of time that the deficit was less than 0.2 mg/L.

To interpret project impacts on the Pueblo Reservoir (Ortiz and Miller, 2009; Ortiz, 2013) using W2 modeling results, the researchers divided the reservoir into epilimnion and hypolimnion and then looked at the annual median and 15th percentile of DO values. Scenarios were compared by the differences in these statistics.

Jones et al. (2011) looked at the timing, depth, and extent of anoxia of 235 reservoirs in Missouri. Ortiz and Miller (2009) evaluated the length of the anoxic season as part of interpreting model results.

Many of the modeling studies evaluated DO time series in calibration and comparing scenarios. Examples include:

- Lake Washington recovery assessment (Cerco et al., 2006).

- TMDL modeling for the Prettyboy and Loch Raven reservoirs in Maryland (ICPRB, 2006). This report also compared cumulative frequency distributions of observed and simulated DO concentrations for average surface and bottom conditions.

- East Canyon TMDL modeling (Miller, 2010).

- Klamath River modeling (Tetra Tech, 2009a).

DO spatial analysis

DO can vary widely over spatial dimensions – by depth from the surface to the bottom; longitudinally from the riverine zone to the lacustrine zone, and laterally from the pelagic to littoral zones. At the same time it is challenging to represent the variability over these three dimensions with limited resources for monitoring. And as intensive monitoring increases spatial resolution of DO values, methods are needed to characterize spatial patterns in simple terms and visually present those patterns.

Studies commonly use separate zones of the reservoir for analyzing DO. Using some or all of the three vertical layers (epilimnion, metalimnion, and hypolimnion) is a standard practice. Some studies also use the longitudinal zones (riverine, transition, lacustrine) or a combination of vertical and lateral zones. In some cases alternative zones were defined, such as the American

Falls Subbasin TMDL (IDEQ, Shoshone-Bannock Tribes, EPA, 2012), which assessed the minimum DO in the top 5 meters and bottom 5 meters. Other cases of how this approach was applied are noted throughout the presentation of results.

One method of characterizing DO levels is through depth- or volume-weighted averaging. Volume-weighted average DO has been used for analyses of Lake Spokane in studies going back to the 1980s. Most recently, Welch et al. (2015) used volume-weighted average DO from monitoring data to evaluate DO recovery in the reservoir. This method is also often used for evaluating modeling results. The DO TMDL (Moore and Ross, 2010) used volume-weighted averaging below the epilimnion (9 meters or deeper). This method was also used in analyses by Brett et al. (2016) and Wells and Berger (2016).

Some studies chose to analyze depth-averaged DO values. Examples include the American Falls Subbasin TMDL (IDEQ, Shoshone-Bannock Tribes, EPA, 2012) and Klamath River TMDL modeling (Tetra Tech, 2009b).

Several TMDLs use the volume or depth which is anoxic or below a threshold. The Snake River TMDL (IDEQ and ODEQ, 2004) looked at the percent of volume below the criterion of 6.5 mg/L over the modeled year (based on 1995 conditions – a 16th percentile high flow year) in 5 different zones (riverine, transition, epilimnion, metalimnion, and hypolimnion). The Deer Creek Reservoir TMDL in Utah (PSOMAS, 2002) used a target of 50% of the water column above the criterion of 4.0 mg/L.

Other studies also applied similar metrics. The analysis of National Lakes Assessment data by Yuan and Pollard (2015) looked at the extent of hypoxia using the percentage of depths less than 2.0 mg/L. Jones et al. (2011) included the depth and extent of anoxia in their assessment of 235 Missouri reservoirs.

Data graphics

A variety of methods have been used to display DO data over time and space and compare observed to model results.

- Time series and profiles (e.g.; Cerco et al., (2006); Cusimano, (2004); Embrey et al., 2012; Hart et al. (2012); Hudson and Vandergucht, 2015; ICPRB, 2006; Ortiz and Miller, 2009; Stevens, M.R., 2003).
- Box-and-whisker plots (Cerco et al., 2006; Embrey et al., 2012; Hudson and Vandergucht, 2015; Stevens, M.R., 2003).
- Isopleths, contour lines, or color contours – DO plotted as lines of equal concentrations or colors in a graph of length versus depth or time versus depth (DeGasperi, C., 2013; Hudson and Vandergucht, 2015; IDEQ and ODEQ, 2004; Nürnberg, 2004). An example is provided in Figure 3.

Figure 3. Color contour plots of Lake Sammamish dissolved oxygen based on routine monthly winter and twice monthly spring-fall sampling from 1995 to 2002. From: DeGasperi, C., 2013.

Spatial heterogeneity

A key issue addressed in several articles is addressing spatial heterogeneity of DO values in a reservoir. The need to address seasonal changes is self-evident, but many lake studies base their analysis on just a few monitoring stations from the middle or deepest locations in the lake. The assumption is made that these data are representative and the error from true conditions for the reservoir as a whole is small. However, the error may be larger than assumed, and the assumption may need to be tested.

Longitudinal variability – the riverine, transition, and lacustrine zones – is described in textbooks (e.g. Thornton et al., 1990; Wetzel, 2001) and is commonly addressed in studies. Lake Spokane modeling and monitoring address these zones, and other examples include: Hudson and Vandergucht, 2015; IDEQ and ODEQ, 2004; and Nürnberg, 2004.

Additional complexity in spatial variability may result from conditions in the arms of reservoirs (inundated tributary valleys) and in the shallow littoral zones. Several studies have explored this issue.

Hudson and Vandergucht, 2015 noted the difference in conditions between the main channel of the reservoir they studied and its major arm.

Embrey et al. (2012) conducted a detailed analysis of Lake Tapps, which is a reservoir with a complex configuration of multiple embayments and islands. Their study looked at the variability

between nine different sites in the lake with depths that varied from 3 to 27 meters. The sites showed differences in stratification, nutrient levels, and trophic state. Figure 4.

Figure 4. Dissolved oxygen concentrations measured in the epilimnion (or near surface) and hypolimnion (or near bottom) at Lake Tapps study sites, Washington, July-December 2010. From: Embrey et al., 2012.

Brett and Arhonditsis (2016) raise questions about the magnitude of productivity from periphyton versus phytoplankton in the Lake Spokane model. Given the discussions regarding spatial variability in other articles, this is a source of uncertainty that might be worthy of further investigation. Monitoring to better quantify periphyton spatial distribution and productivity could clarify its relative role in lake productivity. And if enhancements to the Lake Spokane W2 model are pursued, this information could allow for a more accurate and less uncertain representation of periphyton in the model.

For Lake Spokane in general, longitudinal variability is clearly significant through the riverine, transition, and lacustrine zones. The reservoir is fairly deep with steep sides, and there are isolated littoral areas. However, these areas may be widespread enough to add variability to estimates of productivity and respiration. The reservoir does not have major arms, so only a few small tributary mouths are inundated. These likely make only small contributions to variability in the overall reservoir metabolism.

DO cumulative volume

A unique method that was developed for the Lake Whatcom TMDL (Pickett and Hood, 2008) is the Cumulative Volume method (CVM). The need for this approach was described in the report:

Because of changes in lake level, water flow, the lake seiche, thermal stratification, algae levels, and other conditions, measurements show variability and are difficult to pin to a specific location and time. Therefore, it is difficult to make a consistent comparison between a model cell and point in the lake at any given time. Small changes in inflows or evaporation can change the thermal balance and hydrodynamic characteristics. Therefore, conditions in the same cell at the same time in two different model scenarios may differ because of physical processes not directly related to pollutant loading.

The CVM evaluates the cumulative distribution of lake volumes at different DO levels. Model results for lake volumes are pooled spatially and temporally for the analysis. This supports fishery goals, since fish are mobile and can use the entire lake where habitat exists. Therefore the probability of favorable habitat over time and space will likely represent the probability of fish use of that habitat.

The CVM makes use of the availability of model output in discrete cells of known volume. For each cell the mass of DO can be calculated from volume and concentration. The CVM uses the following process:

- June-October was selected as the critical season for DO depletion
- DO was evaluated in each CE-QUAL-W2 model cell. All segments and layers were included on the assumption that fish can freely access any location in the lake if the habitat is suitable.
- For each cell the minimum DO per day of critical season was identified, based on 3-hr modeling intervals.
- All of the cells were then sorted into "bins" of DO (0.01 mg/L increments)
- The volumes of cells were summed for each bin
- This allowed the cumulative volume below DO levels to be calculated and plotted.

An example of the results of a CVM calculation are shown in Figure 5.

- "Full Build Out" represents a future scenario with higher nutrient loading.
- "Full Roll Back" represents a reference nutrient loading scenario with no development.
- A DO increment of 0.2 mg/L is added to the Full Roll Back scenario, based on the Water Quality Standards.
- Areas where the Full Build Out curve is greater than 0.2 above the Full Roll Back curve are highlighted in red.
- The inset graph shows how the differences are graphed for each incremental bin of volumes.

The power of this method is the spatial and temporal pooling of DO data. This realistically takes into account the time and space windows in which the fish move freely. At the same time, the method preserves the temporal and spatial distribution of DO that defines fish habitat.

Similar methods using cumulative distributions of temperature have been used in TMDL studies in Washington and Oregon[1].

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[1] For example: Pend Oreille River TMDL (https://fortress.wa.gov/ecy/publications/SummaryPages/1010065.html); Mainstem Willamette River TMDL (http://www.oregon.gov/deq/FilterDocs/chpt4temp.pdf)

Figure 5. Example of Cumulative Volume method. From: Pickett and Hood, 2008.

Trophic state analysis

The trophic state of a reservoir refers to the relationship of nutrients to algal biomass in a waterbody. In general, increasing levels of nutrients results in increasing levels of algae and a corresponding loss of clarity.

Lakes are classified for their trophic state on a spectrum from *oligotrophic* (nutrient poor, low algal biomass, high clarity) through *mesotrophic* to *eutrophic* (nutrient rich, high algal biomass, low clarity). Extremes cases are termed ultra-oligotrophic (extremely low nutrient and algal levels, exceptionally high clarity – Lake Chelan is a classic example) and hypereutrophic (extremely high nutrient and algal levels with little clarity – "pea soup" conditions). Trophic state characterizations are empirical, and relationships between trophic parameters are rarely linear.

In deep stratified lakes, trophic status drives DO in two principal ways:
- Eutrophic lakes typically have anoxia in the hypolimnion during summer, while oligotrophic lakes may experience little or no anoxia.
- Algal productivity in the epilimnion of a eutrophic lake typically drives wide diel swings in DO, with supersaturated conditions in the afternoon and depressed DO in the early morning. An oligotrophic lake will experience much smaller diel swings in DO.

Carlson TSI

The Carlson Trophic State Index (TSI; Carlson, 1977) is a classic method that has been applied in a variety of studies (e.g. Canavan and Davis, 2005; Cooke et al., 2011; ICPRB, 2006; Koterba et al., 2011; Nürnberg, 1996). The TSI combines measurements of nutrient levels (total phosphorus), algal biomass (chlorophyll-*a* levels), and clarity (Secchi depth).

Because the Carlson TSI has been widely accepted and applied, it offers a way to compare lakes and track improvements over time. Alternative criteria for trophic state have been offered by other researchers, such as Nürnberg (1996). The merits of different criteria are not debated here. The key point would be to use a consistent metric for comparing values over space or time.

Relationship of DO to trophic parameters

To evaluate site-specific trophic conditions, studies may directly evaluate phosphorus and chlorophyll-*a* levels.
- The Snake River – Hells Canyon TMDL (IDEQ and ODEQ, 2004) used a correlation between phosphorus and chlorophyll-*a* to set TMDL targets (Figure 6), and then modeled the effect on DO of meeting the phosphorus load limits.
- Studies modeling and monitoring results for City of Baltimore reservoirs evaluated phosphorus, algal counts, and chlorophyll-*a* along with DO (ICPRB, 2006; Koterba et al., 2011).
- Chapra (1997) describes correlation methods for chlorophyll-*a*, phosphorus, and Secchi-disk Depth.

Figure 6. Chlorophyll-*a* concentration data as correlated to increasing total phosphorus concentration for the Upstream Snake River segment of the Snake River – Hells Canyon TMDL. From: IDEQ and ODEQ, 2004.

Many studies evaluate statistical relationships between DO and trophic parameters:

- Kesler and Verschuur (1996) evaluated relationships between AF and TP.

- Beutel (2003) developed regressions of AHOD, VHOD, AF, and other parameters to chlorophyll-*a*.

- Nürnberg (2004) developed regressions that predict AF from nutrients (annual TP, summer TP, summer TN, TP load) and a morphometric ratio ($z/A^{0.5}$, where z = mean depth and A = lake surface area). Seventy North American lakes were classified to trophic state levels based on summer AF and the morphometric ratio.

- Jones et al. (2011) analyzed the onset of anoxia in 235 Missouri reservoirs, which correlated weakly to trophic state variables (Figure 7).

- Rankovic et al. (2012) presented an "adaptive network-based fuzzy inference system", or fuzzy model, to predict DO in the Gruža Reservoir in Serbia from eight other water quality parameters.

- Chen and Liu (2014) developed an Artificial Neural Network (ANN) [2] model for DO in the Fetsui Reservoir in Taiwan based on eight other water quality parameters. The ANN model outperformed a multiple linear regression model.

- Carpenter and Rounds (2013) conducted a multivariate correlation analysis of DO, other WQ parameters, and algal parameters.

- Yuan and Pollard (2015) used the EPA National Lakes Assessment database to conduct a multivariate analysis of hypoxia in over 1,000 lakes to a suite of physical and chemical parameters. A significant relationship was found between the proportion of hypoxia with chlorophyll-*a*. Lakes were classified into 9 categories based on temperature gradients, elevation, a lake geometry ratio, and Secchi depth. The power of predicting hypoxia varied across the lake categories, with the strongest relationship found in stratified lakes with high Secchi depths and low lake geometry ratios.

Figure 7. Mean dissolved oxygen for all depths below the surface mixed layer averaged by reservoir and month across all summers. Oxygen measurements were increased by 1 mg/L to permit $\log_{10}$ transformation. From: Jones et al., 2011.

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[2] ANN systems learn (progressively improve performance on) tasks by considering examples, generally without task-specific programming. https://en.wikipedia.org/wiki/Artificial_neural_network

Wells and Cole (2002) examined the use of regressions between AF and TP and between chlorophyll-*a* and TP in Brownlee Reservoir, and compared the results to a mechanistic CE-QUAL-W2 model. The found that although the regressions for Brownlee Reservoir matched regression from other North American lakes, the statistical method may allow a regression to have a good fit even if the fundamental processes vary. They also note that "whatever type of model is used for developing a TMDL, it should be applied appropriately with full knowledge of its capabilities and limitations."

Chlorophyll-*a* remote sensing

Remote sensing technology provides potentially powerful methods for assessing chlorophyll-*a*. The principle of this approach is that chlorophyll-*a* is associated with a unique color in the spectrum (green) that corresponds to a specific wavelength of light. Therefore it's possible to develop a model based on a regression of field data to characteristics of spectral reflectance data. Depending on the method used, a large data set can be generated on chlorophyll-*a* patterns that captures spatial variability, seasonal changes, and long-term patterns over years and decades.

Eckhardt (2005) evaluated remote sensing using three technologies: an AVIRIS (Airborne Visible and Infrared Imaging Spectrometer) sensor; the Hyperion sensor aboard the EO-1 satellite; and an ASD (Analytical Spectral Devices) FieldSpec FR spectroradiometer. Data were collected from: Owyhee Reservoir, Oregon; Flaming Gorge Reservoir, Wyoming; Lake Mead, Nevada and Arizona; and Klamath Lake, Oregon. Chlorophyll-*a* sampling was designed to collect composites from lake depths corresponding to the expected light penetration depth for the spectral imagery – typically the top 1.3 or 5 meters.

This study found that:

> *In all cases, the difference in reflectance between a local minimum near 675 nm and a local maximum near 700 nm was used to successfully predict chlorophyll-a concentrations.*

> *The spectral feature near 700 nm was effective in oligotrophic to eutrophic waters, and in waters that exhibited a wide range of suspended sediment concentrations. It was also immune to the effects of sun and sky radiance from the air/water interface.*

Turner (2010) did a study of Oregon lakes, where he compared data from existing chlorophyll-*a* sampling data to LandSat 5 and 7 reflectance data. Figure 8 illustrates results for one of the lakes. The study found:

- Satellite data could identify seasonal blooms missed by monitoring
- The LandSat data identified spatial variability better than monitoring data
- Interannual patterns could be detected from LandSat data
- Trophic status appears to track LandSat color, with a few "false positives" for shallow, high elevation, ultraoligotrophic lakes.

Figure 8. LandSat Band 2 (green) / Band 1 (blue) ratio for Diamond Lake, Oregon, 1999 – 2008. From: Turner, 2010.

Hansen et al. (2015) used LandSat data to evaluate chlorophyll-*a* in five Utah reservoirs. The analysis included spatial distribution within each reservoir, variation across three seasons, and trends over 20 to 30 years. The study evaluated chlorophyll-*a* with statistical measures, trend lines, spatial distribution maps, and z-score images. Figure 9 provides an illustration of the mapping for two seasons. The conclusions of the study state:

Remote sensing data provide valuable information about the spatial distribution of chlorophyll in reservoirs, information difficult or impossible to obtain with field samples because of limited spatial and temporal coverage. Landsat remote sensing data for North American reservoirs exists every 16 days from 1984 to present (weather permitting).

These data can be used to statistically analyze historical trends to represent reservoir measures such as average, maximum, and variance in algal concentrations and to develop visualizations to provide more detailed reservoir descriptions. The spatial distribution maps of chlorophyll can help visualize reservoir behavior, indicating possible problem areas and identifying locations for field sampling.

Primary Production Analysis

As discussed above, the heart of the ecosystem of a reservoir is its "metabolism", that is, the interaction of gross primary productivity (GPP) and respiration (R). Although there are external sources of DO and carbon – the atmosphere, tributaries, groundwater – the generation of DO and organic carbon by GPP (from algae and aquatic vegetation) and loss of DO from respiration and oxidation typically are the dominant drivers of DO dynamics in the reservoir. Therefore, an understanding of this metabolism is central to assessing and predicting reservoir DO levels.

Figure 9. Chlorophyll-*a* distribution in Jordanelle Reservoir, Utah, on 22 August 2002 (left) and 21 May 2003 (right), estimated from LandSat reflectance data. From: Hansen et al., 2015.

Diel DO analysis

The development of multiparameter datalogging meters that can record water chemistry information at short intervals over extended periods of time has greatly enhanced the ability to assess water quality. In particular, these dataloggers (singly or in multiple locations or depths) can be suspended in a lake or reservoir to record diel patterns of DO, pH, and temperature. Methods have been developed to analyze the daily cycles of these three parameters to estimate lake and reservoir metabolism and DO dynamics.

Delta Method and other similar methods

Chapra and Di Toro (1991) developed the "Delta Method", which estimates GPP, R, and reaeration from diurnal DO measurements. The Delta Method (illustrated in Figure 10, and also described in Chapra, 1997) proceeds through three steps:

1. Reaeration is estimated from the time of minimum DO deficit.

2. Photosynthetic production is computed from the DO deficit range and reaeration rate.

3. Respiration is computed from the average DO deficit, reaeration, and photosynthetic production.

Figure 10. (a) Plant primary production and respiration; (b) dissolved oxygen deficit; and (c) dissolved oxygen concentration versus time. From: Chapra and Di Toro, 1991.

Note that (a) shows the half-sinusoidal photosynthesis function along with the two-term Fourier series approximation.

Several approaches have been explored for the Delta Method (e.g. McBride and Chapra, 2005). The method assumes constant respiration, so the variability of respiration during the day is a source of error in the calculation. Also Chapra and Di Toro (1991) note that the method works best when reaeration rates are relative low (<1.0 d^{-1}).

One example from an Ecology study report is Roberts et al. (2012), where the Delta Method was used to estimate GPP, R, and reaeration in the Deschutes River and Capital Lake.

Van de Bogert et al. (2007) used a similar method in their study of the lateral variability of GPP and R estimates in a lake, where they found that mid-lake measurements underestimated total lake GPP and R if littoral areas were not assessed (discussed above).

Coloso et al. (2008) developed GPP and R estimates from continuous monitoring with DO sondes at multiple depths and locations in a Wisconsin lake (discussed above). Two filtering methods were applied to reduce noise in the data: wavelet transforms, and moving average. Variability of R did not show any spatial patterns, but GPP measurements declined with depth. Horizontally estimates of GPP and R were similar. The study notes that if a sonde had been set only at 1 meter, it would have overestimated seasonal GPP by 13% and R by 3% in the upper mixed layer, and underestimated whole-lake GPP by 18% and R by 41%.

Staehr et al. (2010) explored sources of variability in estimating GPP and R from diel oxygen measurements. Variables that drive or affect the calculation include: DO, water temperature, mixed layer depth, latitude, day of the year, barometric pressure, salinity, wind speed, and irradiance. To understand the assumptions and uncertainties in estimating whole-system GPP and R, several factors need to be considered:

- The depth where a sampling meter is placed. A depth representative of productivity in the mixed surface layer is needed for accurate estimation of GPP.
- The effects of wind or current on mixing.
- The frequency of meter measurements. The study found that "a minimum logging frequency of 30 min was sufficient to capture metabolism at the daily time scale." Higher frequencies might be necessary if there are sources of variability on a finer scale, such as physical mixing.
- The number of consecutive days monitored. The study found that 3 days were sufficient to characterize the weekly average within 20%.
- The assumption that R is constant can increase the sensitivity of the method to wind mixing in oligotrophic lakes, and can result in an underestimate of R.

Table 2 is reproduced from Staehr et al. (2010).

Table 2. Advantages, uncertainties, and assumptions associated with the diel-oxygen technique

Advantages	Uncertainties	Assumptions
Measures all system components	Air-water flux difficult to quantify	Equal respiration during light and darkness
Easy to collect data	O_2 method misses anaerobic R	Sensor detects changes in the entire mixed layer
Avoids bottle effects	O2:C conversion problems	
Provide daily rates of GPP, R, and NE	Physics may obscure biology	
	Horizontal, vertical and temporal heterogeneity due to variable zone of influence on DO sensor	

Forget et al. (2009) collected depth-integrated samples from two Canadian Shield lakes in Quebec every six hours for 14-48 hours during four surveys in June through August. Water samples collected in clear and dark bottles were incubated with light and temperature conditions reproduced in the laboratory to determine productivity and respiration rates from changes in DO from the initial ambient conditions. Other samples were analyzed for chlorophyll-*a* and bacterial abundance. The study documents the daily variability in GPP, R, and algal biomass that has significance for the timing and representativeness of sampling. The diurnal variability in respiration and the GPP:R ratio provides insights into the implications of assuming these values are constant over the day.

Diel DO analysis programs

Diel DO analysis methods are widely used, and researchers have programmed many variations of the method into spreadsheets. Ecology offers a program called the River Metabolism Analyzer, or RMA[3]. RMA is described as:

An Excel workbook tool to apply four methods to analyze continuous monitoring data from a stream for stream metabolism and reaeration. This tool can be used to solve for gross primary production, respiration, reaeration, and limitation due to light, temperature, nutrients, and to predict response to parameter changes with the following methods:

- *delta method to solve for reaeration, gross primary production, and respiration*
- *night-time regression to solve for reaeration and respiration*
- *inverse modeling to solve for gross primary production, respiration, reaeration, light limitation, and temperature limitation*
- *predictive modeling to evaluate model response to changes in any model parameters, including nutrient limitation*

RMA has been used in studies of rivers and streams throughout Washington and elsewhere in the United States. It has also been used for analysis of an estuary in Puget Sound, so conceivably it could be used in a lake or reservoir as well.

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[3] Available on Ecology's website: https://ecology.wa.gov/Research-Data/Data-resources/Models-spreadsheets/Modeling-the-environment/Models-tools-for-TMDLs

Other researchers have created modeling packages that estimate GPP and R from continuous diel DO data. One example is the *LakeMetabolizer* package proposed by Winslow et al. (2016). This package includes 5 different metabolism models using a variety of statistical approaches, including linear regression, maximum likelihood, Kalman filter, and Bayesian statistics.

An enhancement of the diel DO method has been proposed by Honti et al. (2016). They couple continuous DO and chlorophyll-*a* fluorescence time series in a Bayesian framework to determine daily cycles of GPP and R. Their model can simulate both heterotrophic and total respiration, and predicts algal biomass from fluorescence. They applied the model to three lakes of varying morphology: one wide, shallow, and hypereutrophic; one narrow, deep, and mesotrophic with stratification; and a third mesotrophic lake of intermediate size. An analysis of model error provided insights into the limnological processes in the lakes.

Diel isotope analysis

An enhancement to diel DO methods is through the use of the ^{18}O isotope. Photosynthesis generates DO with isotope ratios identical to the surrounding water. However, aerobic respiration consumes ^{16}O preferentially over ^{18}O, thus changing the ratio of $^{18}O{:}^{16}O$. Figure 11 illustrates how ^{18}O levels decline with photosynthesis and increase with respiration, while percent saturation of total DO follows an opposite pattern. In addition, "O_2 sources have naturally distinctive ^{18}O values", which makes ^{18}O a "sensitive tracer of changes in ecosystem metabolism and function" (Venkiteswaran et al., 2007).

Tobias et al. (2007) explored this method by comparing the diel DO monitoring method to three ^{18}O isotope methods. This study identified uncertainties in the different approaches and recommended methods to reduce uncertainty and improve estimates. The difference in the calculated productivity between the assumption of a constant respiration rate and a rate that varied during the day ranged from negligible to approximately 30%.

Venkiteswaran et al. (2007; 2008) developed a dynamic stable isotope model to apply the ^{18}O isotope method, dubbed the photosynthesis–respiration–gas exchange model, or "PoRGy". Six key parameters were identified as drivers of diel DO saturation and ^{18}O fraction: GPP, R, gas exchange, respiration fractionation ratio, ^{18}O content of water, and temperature. The PoRGy model was tested against field data from several sites, where it determined the site-specific GPP, R, and gas exchange rates and matched diel DO and ^{18}O data.

Figure 11. Field data (black dots) with 1 SD error bars (±0.2% and ±0.2‰) and PoRGy model (grey line) diel data from the South Saskatchewan River from 14 to 15 July 2004. From: Venkiteswaran et al., 2007.

Equilibrium saturation is shown as dotted lines in the temporal figures and air-saturated water (ASW) is shown in the cross-plot.

Venkiteswaran et al. (2015) studied the Grand River in Ontario using ^{18}O data and the PoRGy model. The river is impacted by nutrients from both agricultural and point source discharges. The analysis determined the GPP, R and gas exchange (*k*) values along the river. This provided insights into the metabolic rates in the river, showing that:

> *..as nutrients from the agricultural areas were assimilated and transformed in the upper section of the river, metabolic rates increased. However, k also increased, mitigating the change in the observed diel O_2 and $\delta^{18}O\text{-}O_2$ data. The magnitude of the diel O_2 cycle did not indicate high P and R rates because high k dampened diel changes.* [4]

Holtgrieve et al. (2010) reported on the development of a Bayesian statistical model of diel oxygen, which has subsequently been dubbed "BaMM". The model will:

> *Simultaneously estimate gross primary production, ecosystem respiration, and oxygen exchange with the atmosphere (and their uncertainties) on the basis of changes in dissolved oxygen concentration, water temperature, irradiance, and, if desired, the ^{18}O to ^{16}O ratio ($\delta^{18}O–O_2$).*

BaMM "quantified the underlying physical and biological factors that control oxygen dynamics in these ecosystems". The study notes that ^{18}O data can be included but is not necessary, and that "metabolic and reaeration parameters can be accurately estimated by modeling the transient dynamics of dissolved oxygen concentration alone in relation to daily changes in water temperature and light regime." The model is recommended for "low-gas exchange, high-productivity systems", which characterizes many reservoirs.

Poulson and Sullivan (2010) used diel DO and ^{18}O measurements to assess the metabolism in the upper Klamath River. Four diel sampling events included: hourly recording of temperature, pH, conductivity, and DO with a multiparameter data sonde; and hourly grab samples that were analyzed for water–δ^{18}O, water–δD (ratio of deuterium to hydrogen in water), alkalinity, and DIC-δ^{13}C (dissolved inorganic carbon isotopic ratio). The study applied the PoRGy model and found a "generally good" fit, but noted the effect of varying winds on the gas exchange coefficients. Study conclusions note the large variability of productivity rates observed and the unique hydrologic and biogeochemical characteristics of the river, and make a final observation:

> *This study shows that combined diel measurements of field parameters and stable isotope compositions can be useful to studies of biogeochemical cycles in slow-moving rivers, lakes and reservoirs, which are relatively uncommon in the literature. The results demonstrate how diel isotopic cycling in lakes is likely to be more complex than for turbulent, well-mixed rivers, due to the increased likelihood of heterogeneities and stratification on such a time scale, and indicate a necessity for more intensive monitoring in order to properly characterize the system.*

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[4] "δ" in isotope science is the ratio of the less common isotope to the most common isotope in a sample minus the same ratio in a standard as a percentage of the standard. It measures the relative shift in the frequency of occurrence of an uncommon isotope due to environmental processes.

Parker et al. (2010) evaluated the dynamics of ^{18}O-DO and ^{13}C-DIC in 5 Montana rivers and in a control tank. They found that:

> *A cross plot of $\delta^{18}O$-DO and $\delta^{13}C$-DIC from each stream exhibits a clockwise elliptical pattern which is attributed to the daily changes in the balance of metabolic rates as well as air–water gas exchange. The amplitude of the change in the isotope composition is shown to be directly related to the trophic state of the river and a relationship between net productivity and diel changes in $\delta^{18}O$-DO and $\delta^{13}C$-DIC is presented.*

Carbon analysis

Carbon-14 uptake

A classic method for determining the primary productivity of a lake or reservoir is the use of light and dark bottles with the radioactive isotope ^{14}C added (Wetzel and Likens, 2000). Two bottles are filled with lake water – one clear and one kept dark (such as wrapped with electrical tape). The bottles are spiked with a small amount of bicarbonate labeled with ^{14}C. The uptake of labeled carbon can be measured in phytoplankton, which allows measurement of the total uptake of carbon in the sample. The dark bottle provides a control for measurement of photosynthesis in the clear bottle.

Hypolimnetic CO_2 accumulation

A methodology termed the *hypolimnetic CO_2 accumulation* is described by Wetzel and Likens (2000) and Wetzel (2001). This method uses a detailed carbon budget to assess increases in CO_2 in the hypolimnion as a measure of primary production. In a sense this is a complimentary method to AHOD, since as CO_2 accumulates, DO is depleted. The method requires the measurement of ammonia, carbonate, bicarbonate, and DO in the hypolimnion.

Limitations of the method include:
- The hypolimnion should be well isolated from the atmosphere (typified by a deep, steep thermocline)
- Allochthonous inputs of carbon from outside the waterbody should be small compared to autochthonous internal carbon production
- Loss of carbon via the outlet should be relatively small compared to settling
- Degradation of organic carbon occurs mostly in the hypolimnion or sediment
- Methanogenesis or fermentation to fatty acids is relatively small compared to the creation of DIC
- The dissolution of carbonates to DIC is small (a poor assumption for hard water systems)

Given these limitations and the intensity of sampling required, to justify the use of this method there would need to be a strong need to confirm productivity estimates, and the limitations would need to be minor for the particular waterbody.

Sediment assessment

Sediment respiration and SOD

A key factor in determining the dynamics of DO in a lake or reservoir is sediment oxygen demand (SOD). Although SOD may include the respiration of sediment organisms, typically most of SOD is caused by oxidation of chemical compounds, which can include organic carbon, methane, ammonia, sulfur, iron, and manganese (Chapra, 1997; Bastviken, 2009; Giblin, 2009). In a highly productive system, the key process is the settling of organic carbon from plankton into the sediment and the oxidation of the organic carbon over time. This is particularly significant since the effect of SOD on hypolimnetic oxygen can continue for years (or decades) after productivity levels drop due to nutrient source controls.

Beutel (2003) evaluated hypoxia in nine California reservoirs. Sediment cores were collected and then incubated in the laboratory under controlled conditions. Cores were given several days to stabilize, and then the overlying water was saturated with DO and then monitored periodically with a DO meter. Chamber water was analyzed separately for BOD, so the SOD could be calculated by the difference between the chamber DO decline and the BOD of the overlying water. Three levels of chamber water mixing were evaluated – quiescent, moderately mixed, and highly mixed – to simulate the effect of currents or circulation.

Beutel (2003) found that SOD in the reservoirs mostly exhibited a first-order response, although some samples had relatively flat curves that approached zero-order (linear) declines. Mixing tended to increase SOD levels. Correlations were found between SOD and hypolimnetic anoxia (VHOD and AF), and between SOD and mean annual chlorophyll-*a*. The ratio of SOD:AHOD correlated with hypolimnetic volume, surface area, and mean depth. A relationship was developed to predict SOD from AHOD and the mean depth of the hypolimnion.

SOD is a key parameter in modeling DO in reservoirs. Haggard et al. (2012) collected sediment cores from Lake Wister in Oklahoma. SOD rates measured in the laboratory were an order of magnitude less than the values used in a model of the reservoir. Even assuming the higher SOD rates found by Beutel (2003) under mixed conditions, the measured SOD values were still less than the model values. As a result, the model was predicting greater impacts from SOD and underestimating the impacts of BOD generated by external sources.

Miller (2010) analyzed the effect of assumptions regarding SOD in a CE-QUAL-W2 model of East Canyon Reservoir in Utah. The author warns that zero-order SOD values that vary by segment can produce a good model fit, but may not accurately indicate the source of oxygen demand and will not be responsive to changes in external loading. The interactions of transition zone dynamics, bank erosion, settling of organic material, and SOD can be complex and poorly understood.

Several studies evaluated SOD as part of the Upper Klamath River TMDL studies. Doyle and Lynch (2005) reports on SOD measurements taken from one site in Lake Ewauna and three other sites in the Klamath River above Keno Dam. Measurements were taken with *in situ* chambers placed on the river bottom. Replicate variability from each site was similar to variability between

sites. Measured rates were about 10 times smaller than rates from 10 years earlier. Water column BOD values from control chambers were about double the SOD rates. Combined, these sources of oxygen demand were sufficient to account for hypoxia in the Klamath River from July through October, and could be attributed to algal blooms in Upper Klamath Lake.

Flint et al. (2004) reported on monitoring in the Klamath River, including SOD measurements in the Shasta River (a tributary of the Klamath River). In addition they reviewed modeling platforms and data gaps. They report on the importance of SOD in understanding DO dynamics, and recommended further evaluation of SOD levels in the system.

Rounds and Sullivan (2013) reviewed the CE-QUAL-W2 model used for TMDL development in the Klamath River from Lake Ewauna to Keno Dam. A variety of model inputs were reviewed, and upstream boundary conditions identified as one of the largest sources of uncertainty. The maximum SOD rate was originally set at 3.0 $g/m^2/d$, which was at the upper end of measured values. The model was refined by changing the SOD temperature dependence rate to reduce its influence in autumn, winter, and spring. The rate was also reduced to 2.0 $g/m^2/d$ during one year, but the report notes that "a 50-percent decrease in the SOD rate over a 2-year period, however, is not likely to be mirrored by field measurements, so this change may be compensating for some process that is not represented correctly in the DO budget for the current conditions scenarios."

The two approaches to direct measurement of SOD – laboratory analysis of cores and *in situ* measurements with a chamber –have their advantages and disadvantages. The laboratory core method allows a controlled setting for temperature and flow rates, but involves disturbance of the sediment to collect the samples. Therefore, laboratory core measurement could be viewed as measurements of "potential" SOD.

In situ methods involve less disturbance of the sediment but are logistically more challenging. Both methods enclose sediment and therefore likely alter measured values from natural rates. In addition, spatial variability may be high and the representativeness of measurements may be difficult to assess. Therefore, some flexibility is appropriate in applying those rates in modeling.

The Lake Spokane model used to develop the DO TMDL used zero order SOD rates that varied spatially in combination with a first-order rate. No direct SOD measurements were made to set values. During the 2009 update of the Lake Spokane W2 model, sediment variable stoichiometry and kinetics were added to the model (Berger et al., 2009), which included a sediment carbon compartment.

Zero-order SOD rates in models can be estimated from: 1) calibration; 2) AHOD; or 3) direct measurements (Chapra, 1997). Literature values appropriate to the system can also be selected. In Lake Spokane, the DO TMDL adjusted SOD rates as part of calibration to match predictions to DO profile data. The total effective SOD would be considered the total of the first order and the zero order sediment oxygen demand rates.

For the DO TMDL, SOD rates in Lake Spokane were lowered in the final TMDL to represent a future response to reduced nutrient loading and algal biomass. This is the only alternative available for addressing zero-order SOD (Chapra, 1997), and is a common method in TMDL

modeling. Brett and Arhonditsis (2016) commented that "it is important that a systematic and repeatable algorithm be developed for Lake Spokane that couples the SOD rates used in the model to the trophic state of the reservoir." Running the W2 model for a multi-year scenario with sediment diagenesis module could help to address this issue.

Sediment phosphorus diagenesis

One of the most significant questions surrounding the trophic status of reservoirs and lakes is the source of phosphorus that feeds algal growth. Many studies explore the relative contributions of allochthonous (external) loading and autochthonous (internal) loading. Internal loading consists of the phosphorus stored in sediments, which is released as dissolved inorganic P primarily when the sediment-water interface becomes anaerobic. This anaerobic release is often the most significant part of internal reservoir loading.

This loading may be restricted to the hypolimnion while stratification occurs, but becomes available during turnover when the reservoir becomes fully mixed. Internal loading from sediments can be augmented by external P sources, since external sources throughout the year can settle to the sediments and feed internal loading that promotes algal growth in the spring through fall. In addition, recycling of nutrients from the sediments to the water column and back to the sediments can allow internal loading to support eutrophic conditions long after external loading has been reduced.

The chemistry of phosphorus diagenesis in the sediments is complex, and details are provided by many sources (e.g. Wetzel, 2001; Giblin, 2009). P reaches the bottom sediments from the settling of algae and suspended sediments. P can then be adsorbed onto clays and aluminum or ferric hydroxides; and co-precipitate with iron, manganese, and carbonates. When anaerobic conditions occur at the sediment-water interface, release of P can occur rapidly through the reduction of manganese and iron complexes. Bacteria and sulfur can also play a role in the cycling of P from the sediment to a dissolved state in the water column.

Internal loading studies

Given the critical role of sediments in storing and releasing phosphorus, studies have evaluated these processes. However, due to the complexity of the processes and difficulty in direct measurement, methods vary and results have been uncertain.

In many cases, reservoir profile monitoring and modeling of the P budget provides an estimate of internal loading. Miller (2010) evaluated the W2 model of the East Canyon reservoir. Based on an analysis of reservoir hydraulics and P concentrations in the stratified and fully mixed lake and in the river downstream of the dam, he concluded that the model predicted P cycling very well.

Koterba et al. (2011) presented a more challenging situation. A review of monitoring of reservoirs serving the City of Baltimore explored the uncertainty in sediment P release rates. Four studies were cited:

- A study that concluded that P was released by sediments but that it didn't contribute to algal blooms because stratification made P unavailable during the growing season, and algal

blooms did not occur during turnover periods when P mixed to the surface. However, this study was based on limited data that were not representative of conditions spatially or temporally.

- A study that found elevated P in deep water at levels that suggested sediment release.
- A study that found elevated P and iron in sediments.
- A study that that found anoxic conditions in the reservoirs but also found nitrate in the hypolimnion. Nitrate could serve as a preferred electron acceptor and prevent the release of phosphorus. However, the lack of sufficient data limited the ability to draw general conclusions.

These four studies suggested that P release could have been occurring and stimulating algal blooms, but did not provide an overall understanding of P cycling over different seasons and under varying weather and flow conditions.

Cooke et al. (2011) evaluated phosphorus loading in Oklahoma's Tenkiller Reservoir. Sediment release rates were calculated from concentration differences, using different methods for the riverine, transition, and lacustrine zones. The riverine and transition zones were assessed by increases in P compared to inflow levels, taking into account flows, volumes, and surface areas. Lacustrine TP release was calculated from the change in TP concentrations in the hypolimnion. Internal loading was found to be about 16% of total loading, and its effect was strongest on the riverine and transition zones, contributing to eutrophic or hypereutrophic conditions in these areas.

Sediment core studies

Two studies – Haggard and Patterson (2012) and Steinman and Ogdahl (2015) – used sediment cores to directly assess P release rates. Both studies were comparing measured rates to the sediment release rates used in water quality models of the reservoirs. Interestingly, both studies found that measured rates were far lower than rates assumed in the models, with the implication that watershed source control needed to be the focus of restoration activities.

Haggard and Patterson (2012), as part of their study of Lake Wister in Oklahoma, collected six sediment cores from 3 sites – two sites in deep areas and one in a shallow headwater area. For each site, one core was aerated and one core purged with a nitrogen-carbon dioxide mixture. Samples of the water column were collected at 1 to 3 day intervals over a 10 day incubation and tested for soluble reactive phosphorus (SRP – a laboratory test commonly used to measure dissolved inorganic phosphorus). Levels of SRP in replacement water were measured and then purged again before incubation continued.

Results showed P release rates that were about twice as high for the anaerobic samples than for the aerobic samples at the two deep sites. The shallow site showed no difference. The mass of P released correlated with dissolved Fe and Mn levels in the incubated samples. Overall, P release rates were an order of magnitude lower than values used in an earlier model, and as noted above measured SOD rates were also an order of magnitude lower than model values. The study conclusions stated:

The previous modeling report … suggested that internal P sources were dominant in the reservoir nutrient budget, and that this large source precluded the development of a watershed-based strategy to reduce P inputs from external sources. This study illustrates the importance of acquiring empirical measures of SOD and SRP release rates to parameterize reservoir models, rather than relying on what might appear to be reasonable parameter estimates as calibration tools.

Steinman and Ogdahl (2015) studied internal P loading in Bear Lake, Michigan. A TMDL for this lake set targets for external and internal P loading, and a target for growing season concentrations in the lake. The TMDL set internal loading based on empirical calculations from sediment chemistry measurements.

Four locations were sampled on four different dates, and six sediment cores collected during each survey at each site. Cores were incubated at temperatures that matched near-bottom lake conditions. Three cores from each site were aerated, while three were purged with a nitrogen-carbon dioxide mixture. Eleven water samples were collected from the water over the cores over a 27 day incubation and tested for total P (TP) and SRP. SRP values were below detection, so the analysis used TP.

Anoxic TP release rates were significantly higher than oxic release rates. Rates were highest in August, somewhat lower in July, much lower in October/November, and lowest in April. Anoxic release rates had no significant difference between sites.

Five scenarios were evaluated to assess internal loading, ranging from fully oxic conditions to fully hypoxic conditions. The TMDL internal load of 702 kg/year was closest to the assumption of fully hypoxic conditions (876 kg/year). However, field measurements have shown that the lake is typically fully oxic, or has hypoxia only near the sediments. Therefore, the most likely internal loading based on measurements was between 100 and 200 kg/year.

Because the TMDL target for internal loading is 146 kg/year, these results suggest that internal loading target is being met. As a result, the study recommends that "management efforts aimed at reducing the water column P concentration to reach the TMDL target should instead be directed at controlling the external P load."

Paleolimnological sediment cores

From the initial impoundment of a reservoir, materials begin to settle in the lake and build up in the sediments. Over time, layers of materials are deposited that provide a record of the ecology of the waterbody. Wetzel and Likens (2000) describe methods for analyzing sediment cores to evaluate trophic status from the layers in the sediment. By looking at TP concentrations, pigments, chlorophyll-*a*, and diatom frustules, long-term patterns of nutrient loading and algal biomass can be evaluated.

Paleolimnological sediment cores are also used for other parameters. Cores have been collected from Lake Spokane as part of PCB deposition studies.

An excellent resource is a series of technical articles entitled "Tracking Environmental Change Using Lake Sediments." Three volumes of particular relevance to this review:

- Volume 1: Basin Analysis, Coring, and Chronological Techniques (Last and Smol, 2001a)
- Volume 2: Physical and Geological Methods (Last and Smol, 2001b)
- Volume 3: Terrestrial, Algal, and Siliceous Indicators (Smol et al., 2001)

Volume 4, which was not reviewed, addresses zoological indicators such as crustaceans, mollusks, insects, and fish.

In Volume 1, Part II provides detailed information on "core acquisition, archiving, and logging techniques." This includes: a review of coring devices; lake deployment platforms; core logging devices; and magnetic susceptibility methods.

Volume 1, Part III describes eight chronostratigraphic techniques. Some that are potentially relevant to Lake Spokane application are:

- Varve counting (identifying and counting annual sediment layers, much like tree rings)
- Tephrochronology (tracks deposition from volcanic events, good for correlating cores)
- Radioactive lead isotope dating (^{210}Pb from natural background and human sources such as fallout from weapons testing and Chernobyl reactor meltdown. Hanford releases could be a signal for this method.)
- Luminescence dating (based on when quartz or potassium feldspar was last exposed to the light – works well with loess sediment)

Volume 2 includes:

- Physical lithostratigraphy techniques. This includes digital imaging, x-radiology, and textural analysis.
- Mineralogical and geochemical indicator techniques. Along with chemical and mineral assessments, this includes: fluid inclusions; mineral magnetism; organic matter; persistent organic pollutants (such as PCBs); near-infrared (NIR) spectrophotometry (can reconstruct water chemistry, such as TP and total organic carbon (TOC), or "fingerprint" sediment layers as a screening tool);
- Stable isotope techniques. This includes: carbonate or cellulose analysis with isotopes of carbon and oxygen; and C:N ratios with ^{13}C and ^{15}N.0

Volume 3 explores biological indicators. Methods of particular interest to assessing Lake Spokane could include:

- Charcoal (fire proxy)
- Organic microfossils, such as green algae spores and cell walls, cyanobacteria akinetes, resting eggs of rotifers, testate amoebae, diatom frustules, chrysophyte scales and cysts
- Sedimentary pigments, such as chlorophylls and carotenoids, and other biological pigments and their derivatives.

Another method with particular relevance to DO assessments is the assessment of chironomid (midge) subfossils in sediments. Quinlan and Smol (2001) developed statistical relationships between chironomid head capsules DO measures. The strongest variables included end-of-

summer volume-weighted hypolimnetic oxygen concentration and bottom oxygen concentration. Using oxygen inference models developed from these relationships, historical DO conditions could be reconstructed from chironomid profiles, which showed responses to historic land clearing and logging.

Verbruggen et al (2011) studied subfossil remains of chironomid larvae in 28 large, deep stratified lakes in Europe. Correlations were found between chironomid assemblages and temperature, TP concentration, and DO availability. A reconstruction of historic TP levels using subfossil chironomids demonstrated that the method could provide quantitative estimates of past nutrient concentrations in deep, stratified lakes.

A case study

An example of a sediment core study is Moos and Ginn (2016), where they evaluated sediment cores for Musselman Lake, a kettle lake in Ontario. The objective of the core sampling was "to put … current environmental conditions in perspective, account for long-term limnological trends, and develop a sustainable lake management strategy". A 37.5 cm long core was extracted from the deepest part of the lake. The core was sampled into 0.5 cm intervals and subsamples collected for diatom analysis. To reconstruct nutrient status and water clarity, diatom valves were identified to the lowest possible taxa; chrysophyte cysts were also enumerated, but not identified. In additions, layers were analyzed for charcoal (to reconstruct fire history), for stable nitrogen and carbon isotopes (to track human influences), and radiometric dating (to verify the timing of changes).

The sediment core analysis reconstructed approximately 300 years of the lake's ecology. The temporal zones were identified. Conditions appeared to be stable from the early 1700s until the mid-1800s. Then the species assemblages and charcoal signal shifted, apparently from the settlement of the area and development of small farms and seasonal recreation homes. This period also had steadily increasing P levels as the use of fertilizers and discharges from septic systems increased. A third shift occurred beginning about in 1990 which appears to be the result of suburban development reaching the lake, with associated permanent housing and utilities. The article concludes:

> *Musselman Lake receives P inputs from 3 sources: surface run-off from the catchment (as indicated by increasing Cl^- concentrations), septic effluent from residences (as indicated by increased δ15N values and inputs estimated to be ~2% of lake volume per year…), and re-release of P from lake sediments (suggested by a layer of deepwater algae).*

Phytoplankton assemblages

Algal ecology

At the heart of the aquatic ecosystem of lakes and reservoirs is the phytoplankton community, which takes up nutrients and sunlight to create carbohydrates, and alters DO levels through respiration and photosynthesis. How phytoplankton affect DO is highly dependent on the species assemblages present. Typically a lake or reservoir has innumerable different types of algae present at any given time, but over the course of the growing season there may be several periods

when the populations of different dominant types of algae peak. This seasonal shift in dominant algal types is termed *algal succession*. A common succession pattern is to see a bloom of diatoms in the spring, a bloom of green algae mid-summer, and a bloom of blue-green cyanobacteria and diatoms in the late summer or early fall.

One conceptual model for algal succession, called the PEG (Plankton Ecology Group) model, was reported by Sommer et al. (1986). The PEG model looks at "24 sequential statements which describe step by step the seasonal events which occur in the phytoplankton and zooplankton of an idealized 'standard' lake." Distinct patterns were discerned between lake with high or low levels of summer algal biomass, which are linked to the roles of physical factors, trophic status types, nutrient limitations, zooplankton grazing pressure, and fish predation on zooplankton.

The PEG model was revisited by Sommer et al. (2012), in which they identified other complicating factors such as "overwintering of key organisms, the microbial food web, parasitism, and food quality". Although attempts have been made at applying the PEG model in numerical models, its principal value is that it illustrates the complexity of phytoplankton abundance and succession.

Another attempt at a structured analysis of phytoplankton assemblages was made by Reynolds et al. (2002). This study identified 31 phytoplankton assemblages that characterized "functional associations" based on "commonly shared adaptive features". A wide variety of traits were identified in terms of tolerance of habitat features, which included: stratification and mixing, trophic level, clarity and light levels, pH, macro- and micro-nutrient composition, lake size, retention time and flushing rate, filter feeding, grazing rates, and other factors. Again, the principle point of interest is the diversity of lakes and reservoirs and complexity of factors that drive the composition of phytoplankton assemblages.

Assessments of lakes and reservoirs will generally determine the annual cycle of different phytoplankton and zooplankton species. Lehman (1988), in his analysis of recovery of Lake Washington following the removal of wastewater discharges, found significant shift in phytoplankton species. He identified 1969-1975 as a period of recovery when "water transparency increased and algal biomass declined in response to nutrient diversion", corresponding to decreases in chlorophyll-*a* levels and hypolimnetic oxygen depletion.

Although there were shifts in phytoplankton species during initial lake recovery, among zooplankton the copepod herbivore *Diaptomus ashlandi* remained dominant. However, in 1976 *Daphnia* species became the dominant zooplankton, as reported by Lehman (1988) who cites Edmonson and Litt (1982). Water transparency approximately doubled with the zooplankton species shift. They attributed the change to a decline in the predator *Neomysis mercedis*, which in turn may have been caused by increased populations of long-fin smelt, who feed on *Neomysis*. The key finding here is that changes in nutrient loading can cascade through an ecosystem, resulting in changes in food web structure that may take decades to resolve itself.

Cooke et al. (2011) in their study of Tenkiller Reservoir, examined the trends in phytoplankton taxa over many decades. They note that in studies in the 60s and 70s conditions were oligo-mesotrophic with little cyanobacteria observed. A survey in the mid-1980s found blooms of

dinoflagellates, while in the mid-1990's the spring bloom was principally diatoms and summer conditions dominated by cyanobacteria. This trend continued toward phytoplankton species shifts indicating eutrophic conditions, with cyanobacteria dominating in the 2000's.

Modeling of algal taxa

Many studies that used the W2 model for water quality have addressed seasonal cycling of dominant phytoplankton species.

In their data gap review for the Upper Klamath River TMDL, Flint et al. (2004) noted that:

> *A better understanding is needed of the types and populations of algae (periphyton and phytoplankton) in the reservoirs and in the riverine reaches, unless another source of data is available, to determine if the Aphanizomenon in the reservoirs are thriving or slowly dying as they are swept downstream from Upper Klamath Lake. It also is necessary to determine if algal growth is limited by the nitrogen or phosphorus levels, to measure primary productivity, and to assess the adequacy of available nutrient data.*

The Upper Klamath River TMDL W2 model included a "two-state" algal model, which was based on "healthy" versus "unhealthy" populations, and not on a particular species assemblage. In their review of the model, Rounds and Sullivan (2013) described this approach:

> *Healthy algae in the model are converted to an unhealthy state at a user-specified rate that depends on the simulated DO concentration, with a greater rate of conversion at lower DO concentrations. Similarly, the unhealthy algae are converted to a healthy state at a different user-specified rate that increases at higher DO concentrations.*

However, they noted that "the algorithms currently appear to help the model fit the patterns in the available data … but those algorithms are not truly predictive or reliable for certain purposes until they can be tested through well-designed experiments and research." In other words, the available research did not fully support the two-state algae algorithms, which runs the risk of "overfitting" the model.

A report on the TMDL modeling framework for two reservoirs on the Gunpowder River in Maryland (ICPRB, 2006) included the results of monitoring algal taxa. A typical pattern was identified of a spring diatom bloom, a mid-summer green algae bloom, and under certain conditions a bloom of blue-green cyanobacteria in late summer and early fall. Based on this information, the W2 model included three algal groups: a spring diatom bloom; a late summer bloom of either green or blue-green algae; and an undefined winter population. The primary calibration objective was to set the algal growth rates and temperature parameters for the three seasons so that modeled chlorophyll-*a* matched observed peak values. The report expressed confidence that the goals were met by predicting similar seasonal peak concentrations, although the day-by-day timing of the peaks were often offset. In this way a successful linkage was established between phosphorus loading, algal biomass, and DO deficits.

Ortiz and Miller (2009) and Ortiz (2013) reported on their development of a W2 model of the Pueblo Reservoir in Colorado. The objective of this modeling was to compare project alternatives by replicating the seasonal and spatial relationship between nutrients, algal biomass

and dissolved oxygen. In addition the modeling of cyanobacteria supported an assessment of potential public health impacts from toxicity. Their model employed four algal groups, representing blue-green algae (cyanobacteria), green algae, diatoms, and flagellates. Light, water temperature, and nutrient availability controlled biomass of each algal group. In May through September, the highest algal biomass was predicted with greens and blue-greens dominant, while outside this season biomass was lower and diatoms and flagellates dominated.

The W2 modeling study of East Canyon Reservoir (Miller, 2010) included an objective to "qualitatively track seasonal and major long term shifts in algal succession related to phosphorus reductions." To accomplish this, a customized algal succession code was developed for CE-QUAL-W2 version 3.5. This new code was identified as a "research and development" code still undergoing testing. Features of this code include vertical migration and luxury uptake of phosphorus.

The W2 custom modifications presented by Miller (2010) were also applied to modeling of Elephant Butte Reservoir in New Mexico. A review of this model (Buchak, 2011) commented on the modeling of algal processes:

The algal process algorithms
o *capture diurnal, autonomous vertical motion of algal cells;*
o *represent seasonal mortality;*
o *account for phosphorus uptake, algal settlement to a benthic compartment, and subsequent, spring-time release of stored phosphorus to the water column.*

These algal processes are important components of the growth and decay of algal masses and are not currently included in standard CE-QUAL-W2 code
…The literature also attests to the complexity of algal population dynamics
…Working with these algorithms during the code development and testing phase makes it clear that the parameters required to calibrate this version of the model are site-specific and that the simulations are extremely sensitive to the parameter values. These two properties make the model of limited value in a predictive sense.

Bull trout in central Idaho's Deadwood Reservoir were the subject of a study by Weigel et al. (2017). A linked water quality and ecosystem model (ELCOM-CAEDYM) was developed based on water quality data and radio-tagging of bull trout. The four phytoplankton groups dominant in the reservoir were modeled: cyanobacteria, dinoflagellates, diatoms, and cryptophytes. Features of the phytoplankton model included:

- Dynamic nitrogen intracellular stores for dinoflagellates and cryptophytes, and constant nitrogen stores for cyanobacteria and diatoms.

- Constant phosphorus intracellular stores for all groups.

- A phytoplankton loss term to indirectly simulate grazing.

- Active vertical migration was included for dinoflagellates and cryptophytes.

- Cyanobacteria were positively buoyant with a constant upwards velocity and diatoms had a constant settling velocity based on their average size and specific gravity.

The variability and seasonal species shifts of phytoplankton are clearly a key element of understanding reservoir metabolism and DO dynamics. However, the drivers of planktonic

species structure are complex and their interactions and influence on succession are only partially understood. Modeling of phytoplankton biomass for multiple species is challenging and approaches by necessity are simplified. This is an area of ongoing research and model enhancement.

Reductions in external nutrient loading may cause shifts in algal assemblages. For future model development, succession and abundance of algal groups should be assessed to determine whether changes in the parameters and kinetics of the model are warranted to reflect current conditions.

Fish ecology

The temperature-DO squeeze and fish movement

A core purpose of DO criteria is the protection of fish habitat. As was discussed above, a key feature of habitat loss in reservoirs and lakes is the spatial and temporal extent and severity of hypolimnetic DO depletion. Coincident with the growth of hypoxia in a stratified reservoir is the warming of waters in the epilimnion. As a result, surface waters may exceed fish tolerance thresholds for temperature at the same time that deep water are too hypoxic for fish. This has been termed the "temperature-DO squeeze": the volume of mid-elevation waters that are both cool enough and sufficiently oxygenated for fish shrinks during the summer as the hypolimnion gets deeper and surface waters get warmer.

The physical structure of the reservoir in terms of stratification, DO, and temperature can be explored using the modeling and analysis tools discussed above. In addition, many studies have addressed or evaluated the relationship of this phenomenon to fish habitat and abundance. Table 3 summarizes the temperature and DO thresholds which defined species presence from the studies reviewed.

Table 3. Temperature-DO squeeze boundaries (optimal habitat thresholds).

Species	Temperature (ºC)	DO (mg/L)	Citation
Cutthroat trout[2]	18.0	3.0	Baldwin et al., 2002
Kokanee[1]	17.0	4.0	Berge, 2009
Rainbow trout[1]	21.0	2.5	Swales, 2006
Mysis[2]	17.0	3.0	Johnson and Martinez, 2012
Kokanee[1]	17.0	3.0	Klobucar and Budy, 2016
Bull trout[2]	18.0	6.0	Weigel et al., 2017
Warm water species[2,3]	24.0	5.0	Jones et al., 2011
Blueback herring[3]	25.0	2.0	Nestler et al., 2002
Striped bass[2]	24.0	4.0	Bettoli, 2005
Smallmouth bass[1]	29.0	5.0	Welch et al., 2011
Walleye[1], striped bass[2]	24.0	5.0	Welch et al., 2011
Largemouth bass[1]	28.0	1.5	French et al., 2017

[1] Found in Lake Spokane

[2] Found in Washington State, but not in Lake Spokane

[3] Not found in Washington State

Jones et al. (2011) surveyed temperature and oxygen data for 235 Missouri reservoirs. The study evaluated temperature-DO squeeze thresholds for cold- and warm-water fishes (Table 3). In 76% of reservoirs, layers with cool temperatures (less than 20 °C) during July and August were associated with anoxic conditions (DO less than 1.0 mg/L), reflecting conditions in the hypolimnion. In another 13% of reservoirs, temperatures below 20 °C were only found with hypoxia (<4 mg/L). Most reservoirs failed to provide habitat in the lacustrine zones within the optimal thresholds for warm-water fish (<24 °C and >5.0 mg/L), and fish are forced to survive in suboptimal mixed layers, representing about half of the volume in the reservoirs.

Cold water fish

Baldwin and Beauchamp (2002) studied cutthroat trout in Strawberry Reservoir, Utah. Vertical profiles were measured for temperature and DO, and fish were tracked with hydroacoustics and GPS. Trout tended to gather in areas of optimal temperature and were relatively tolerant of DO. As hypoxia grew, they avoided the lowest DO values and moved into warmer surface waters. In general, they avoided DO below 3.0 mg/L and temperatures above 18 °C.

Hansen et al. (2013) further explored cutthroat trout foraging in Strawberry Reservoir. The temperature-DO squeeze reduced prey encounter rates because prey moved into warmer surface waters that the trout avoided. Prey encounter rates peaked at dusk and dawn when surface temperatures were cooler but light levels were still sufficient to ensure visual encounters. The encroachment of hypoxia into the metalimnion forced trout into the warmer surface waters, which increased prey interactions but increased metabolism and food needs.

The effect of the temperature-DO squeeze on kokanee in Lake Sammamish was the subject of a Masters thesis by Berge (2009). The zone of favorable conditions (<17 °C and > 4 mg/L) was found to shrink as summer progressed, reaching 16% of lake volume. This squeeze had adverse impacts on juvenile kokanee by: inhibiting growth due to warmer temperatures; reducing their access to their preferred diet of *Daphnia*, which are more tolerant of higher temperatures; and increasing predation by cutthroat trout due to higher fish densities.

Kokanee in Lake Sammamish was also the subject of the study by DeGasperi (2013), who found results similar to Berge (2009): only 20% of lake volume was available to kokanee in a layer between 10 and 12 meters in depth. Figure 12 illustrates the temperature and DO patterns over depth and time, and the "squeeze" between the thresholds. This study evaluated water quality with 2-D and 3-D models under scenarios of future warming, and found that stratification would be stronger, start earlier and end later, causing a decline in summer habitat due to an intensified "squeeze".

Johnson and Martinez (2012) studied the interactions of kokanee, *Mysis diluviana* ("opossum shrimp"), and *Daphnia* in Lake Granby, a reservoir in Colorado. The focus of the study was the ecology of the *Mysis* shrimp, which competes with kokanee for *Daphnia* as a food source. Conditions that are unfavorable for *Mysis* tend to be favorable for kokanee, who get greater access to *Daphnia* for forage, while abundant populations of *Mysis* tend to favor lake trout. The temperature-DO squeeze was evaluated for *Mysis*, and in this case hotter, drier years with greater reservoir drawdown decreased habitat through the squeeze. This made conditions less favorable

for *Mysis* and increased biota density and predation rates, which in turn was favorable to kokanee.

Figure 12. Isopleths of temperature and dissolved oxygen based on data from the central monitoring station in Lake Sammamish, 1995-2002. From: DeGasperi, 2013.

Swales (2006) reviewed literature for factors affecting the abundance and distribution of rainbow trout. The "habitat squeeze" is discussed in detail, and the report concludes that "water quality conditions, specifically the concentration of dissolved oxygen and water temperature, appear to be of overriding importance." A 21.0 °C temperature and 2.5 mg/L DO are identified as the upper and lower boundaries that define depths that rainbow trout will inhabit. The study also notes that other factors, such as availability of prey species, can affect trout distribution.

Klobucar and Budy (2016) studied lake trout and their principal prey, kokanee salmon, in the Twin Pots Reservoir in northeastern Utah. Vertical arrays of remote temperature loggers were deployed and vertical profiles monitored with DO-temperature probes. Fish populations were assessed with gill nets and hydroacoustic surveys. Fish surveys identified thresholds of 17 °C and 3.0 mg/L DO, which limited the distribution of kokanee. The study found that late summer conditions had the smallest habitat volume for kokanee, due to reservoir drawdown and high surface temperatures. During these conditions prey (kokanee) densities and encounter rates were highest, and predator capture success rates needed for optimal growth were lowest.

The modeling by Weigel et al. (2017) of bull trout in Deadwood Reservoir included an analysis of available fish habitat caused by the annual climate patterns and flow regimes and the resulting temperature and DO conditions. Dry climate conditions and higher outflows tended to produce deeper warm temperatures and shallower hypoxia. However, wet years or low outflows tended to increase anoxia but restrict hypoxic conditions to deeper depths. The resulting combination of

conditions is presented in Figure 13 as volume of suitable habitat (≤18 °C and DO ≥ 6 mg/L). The combination of wet year and low outflow reduces suitable habitat to about 30% of total volume, while a dry year with high outflow produces over a month with no suitable habitat.

Avista (2017) used a habitat volume method to evaluate habitat for their 5-year assessment. Volumes that were below 18ºC and above 6 mg/L DO were evaluated, based on reported rainbow trout habitat needs. Conditions at six monitoring stations were assessed for seven sampling years (2010-2016). Conditions varied inter-annually with severe loss of habitat in some years (e.g. 2015) and relatively mild losses in other year (e.g. 2011).

Figure 13. Comparison of the habitats volumes for bull trout in Deadwood Reservoir, Idaho. From: Weigel et al., 2017.

Volumes are normalized by the total lake volume in percent (%) and based on simulated water temperature and dissolved oxygen values for validation and six scenarios – dry, average, and wet years (red, blue, and green lines); and low or high outflows (dashed or solid lines). The annual total (January–December) and habitat reduction period (shaded area) of habitat values are indicated in parentheses as percent (%) of the lake volume.

Warm water fish

Other studies looked at tolerance of warm-water fish. Nestler et al. (2002) evaluated the movement of blueback herring in J. Strom Thurmond Lake, which straddles the Georgia-South Carolina border. Fish distribution was assessed with hydroacoustics and gill netting. Temperature thresholds for fish movement were identified as 25 ºC and 2.0 mg/L DO.

Bettoli (2005) studied striped bass in the Melton Hill Reservoir in Tennessee. Twenty-two fish were radio-tagged and were tracked for approximately a year. Vertical profiles of temperature and DO were collected on tracking dates. Fish were found to generally avoid extreme hypoxia

(<4 mg/L), which occurred rarely, or temperatures above 24 $^{\circ}$C. Fish movements also appear to be driven by prey availability, spawning location, and site fidelity.

Conditions in Tenkiller Reservoir for warm-water fish were studied by Welch et al. (2011). For the three years studied, suboptimal conditions for smallmouth bass (DO >5 mg/L, temperature <29 $^{\circ}$C) were present in less than 10% of the lake's volume for almost 2 months in 2005 and about 3 weeks in 2006. In 2007, 10% of volume was the minimum available in late August. Smallmouth bass are relatively intolerant of eutrophication, and their populations have been relatively low in Tenkiller Reservoir as compared to less eutrophic reservoirs in the region. For about 3 months in all years studied, conditions throughout the reservoir were worse than suboptimal for walleye and striped bass; stocking attempts for these two species have generally failed.

Largemouth bass are relatively tolerant of eutrophic conditions. French et al. (2017) conducted laboratory studies of foraging behavior for this species. Control and treatment tanks were designed to create cold, anoxic water in the bottom half and warm oxygenated water in the top half. Behavior was observed as prey were introduced in the top, bottom, both, or neither. Largemouth bass would pursue prey at DO levels as low as 1.5 mg/L, but prey consumption levels were far lower. The temperature-DO squeeze did not appear to be an absolute barrier, but it still affected forage and growth.

Fish volitional movement modeling

Several studies have explored modeling fish behavior to predict their movement based on environmental stimuli. The major effort was an "Eulerian-Lagrangian-Agent" model (ELAM) of fish volitional movement developed for blueback herring in South Carolina's J. Strom Thurmond Reservoir (Goodwin, 2000; Nestler and Goodwin, 2002; Nestler et al., 2002; Gustafson et al., 2003; Nestler et al., 2005; Goodwin et al., 2006). ELAM is a water quality model that combines two methods: a conventional method, where water movement and biochemical transformations occur within a fixed grid (the *Eulerian* approach); and a model from a fish's point of view, interacting with the water quality framework, but moving through the grid based on volitional rules (a *Lagrangian* approach).

For the modeling of blueback herring, a W2 model was developed for reservoir water quality. Then normalized variables were developed, and weighting factors applied to the variables to balance fish responses to flow and water quality stimuli. The resulting ELAM model was calibrated to the fish location data collected in the field. The strongest factor was temperature (move towards optimum temperature of 15 $^{\circ}$C), then DO (follow increasing gradients of DO up to 6.0 mg/L), and then responses to horizontal and vertical flow velocity. Additional random terms were applied to movement in three dimensions.

Figure 14 illustrates the model results. The squeeze is apparent: temperature weighting factors would tend to drive fish towards the bottom, while DO factors drive them towards the surface. As a result, they cluster in the center. Movement laterally and longitudinally is primarily random with a small influence from velocity.

Figure 14. Visualization of ELAM model results for blueback herring in J. Strom Thurmond Reservoir. From: Nestler et al., 2005.

Yellow dots represent virtual fish, black arrows velocity vectors, blue triangles intersecting tributaries, and the red triangle a major change in the cross-sectional area of the reservoir. The red bar charts indicate the instantaneous responses of fish to various environmental factors (V 5 water velocity, TP 5 temperature, DO 5 dissolved oxygen, and RD 5 random number) for each movement direction (X-direction 5 longitudinal and Z-direction 5 vertical).

A major modeling effort on fish volitional movement has been underway to predict fish behavior as part of passage at Columbia River dams (e.g. Nestler et al., 2007; Goodwin et al., 2006). The focus of this work has been on fish response to hydrodynamic cues, such as flow strength and direction, whole body acceleration, spatial velocity gradients, and pressure. Water quality stimuli could be included but are considered negligible in this context.

Fish bioenergetics models

Bioenergetics models take the objectives of the volitional movement models a step further by evaluating fish growth and interactions with prey and predators. This is accomplished by

evaluating the energy balance of the fish populations as they feed, grow, and respire. Some examples are provided from studies of reservoirs in the western U.S.

Fish growth is generally determined by predator-prey interactions, levels of activity (e.g. for foraging, predator avoidance, and spawning), flow, fish densities, and water temperatures. DO is generally a minor factor, although it is a consideration for fish presence and activity levels. Swales (2006) noted for rainbow trout that "activity is reduced as oxygen concentration drops, even at low temperatures". French et al. (2017), as mentioned above, noted that prey consumption for largemouth bass was reduced when DO levels were low.

Baldwin et al. (2000) developed a bioenergetics model of Strawberry Reservoir in Utah. Surveys were conducted of water quality parameters, zooplankton, and fish (cutthroat trout, rainbow trout, and kokanee). Data helped develop model parameters such as growth rates, thermal history, diet composition, and species abundances. Model results provided detailed information on lake metabolism, trophic interactions, and food web species abundance. DO was a minor factor in fish bioenergetics, although fish avoided low DO, which limited their available habitat. The study authors observe: "defining the role and impact of piscivorous and planktivorous trophic interactions provided information for management decisions regarding stocking strategies, recruitment, carrying capacity, and other food web processes."

Hansen et al. (2013) revisited the Strawberry Reservoir model to evaluate cutthroat trout foraging. The bioenergetics model provided the tool to assess prey encounter rates, metabolism, and growth rates. DO primarily set boundaries on fish presence, sometimes limiting fish access to prey. Fall overturn and the break-up of stratification greatly increased predator-prey encounters.

The study of bull trout in Deadwood Reservoir discussed above (Weigel et al., 2017) was focused on a bioenergetics model. Regarding DO and bull trout growth, the article notes:

> *Although the low DO concentrations persisted for longer during the scenarios that had either wet climatic conditions or low reservoir outflow (0.06 m3 s−1), the cooler water temperatures and higher reservoir elevations provide more benefits to Bull Trout and the reservoir ecosystem.*

Wells (2014) reviewed bioenergetics models for kokanee in Lake Roosevelt and bull trout in Chester Morse Lake, two reservoirs in Washington State. Both models include a W2 water quality model focused on temperature combined with a fish bioenergetics model. The approach used by Nestler et al. (2002) was summarized and a potential application to Brownlee Reservoir on the Snake River explored. Although these models focused on flow and temperature, they demonstrate an approach that could be expanded to include DO.

Hansen et al. (2017) modeled bioenergetics of bull trout and kokanee in Keechelus and Kachess Reservoirs in the Yakima River basin, which included an extensive analysis of the interactions between fish and zooplankton species. This model was based on limnological and fisheries data, and primarily address the impacts of drawdown and water diversions on temperature, fish distributions, and ecological interactions.

Berger and Wells (2017) developed a CE-QUAL-W2 model of Keechelus and Kachess Reservoirs. The models included water depths, temperatures, DO, nutrients, and bioenergetics (from Hansen et al., 2017). However, model boundary conditions and calibration were based on a limited data set. The study report mostly focused on temperature structure and fish growth, and did not report on modeled DO conditions.

Although the two studies of Keechelus and Kachess Reservoirs do not address DO directly they do represent a state-of-the-art approach to modeling the effect of management scenarios on lake ecosystems and the presence and growth of fish populations.

Weather, hydrology, and flow

Key drivers for reservoir ecosystems are weather conditions, hydrology, and flow. Many studies analyze the effects of inter-annual variations in flow conditions on reservoir water quality. Some examples are discussed here.

Nürnberg (2002; 2004) comments on the effect of flushing rates and residence times on driving variability between years. Hypolimnetic DO depletion was found to be correlated with summer inflow and spring and late fall flushing rates in Brownlee Reservoir. High flows in spring delay the onset of stratification, while low summer and fall flows can stabilize stratification.

Ortiz and Miller (2009) compared model results for Pueblo Reservoir for a wet year (2000), an average year (2001), and a dry year (2002). This increased the confidence in model performance over a variety of hydrologic conditions.

Hudson and Vandergucht (2015) studied DO conditions in Lake Diefenbaker, a reservoir in Saskatchewan. They found that high flow events were associated with high turbidity levels. From their analysis of flow, turbidity, and DO, and from other research, they inferred:

> *This represents a major pulse of allochthonous inorganic and organic material to the reservoir bottom.*
>
> *Under such conditions, the benthic decomposition of the settled allochthonous organic load can rapidly drawdown overlying DO in the metalimnion.*
>
> *In addition, the decomposition of the settling organic matter that is trapped in the metalimnion due to the rapid changes in density and viscosity in this stratum, would also add to the loss of oxygen at this depth.*

Dawson et al. (2015) analyzed trends in water quality and quantity for 11 reservoirs in the Brazos and Colorado River basins of central Texas. The Kendall tau statistical analysis (standard and seasonal) was used for trends and Principal Components Analysis (PCA) evaluated interrelationships. Significant trends were identified for increasing precipitation and for decreasing inflows. This apparent contradiction was attributed to a trend in increasing basin withdrawals. DO significantly increased in 2 reservoirs, decreased in 2 reservoirs, and no trends were detected in 6 reservoirs (1 reservoir had insufficient data). Water temperatures increased significantly in 4 reservoirs, decreased in 1, and showed no trend in the other 6. PCA showed temperature and DO varying inversely to each other, which would be expected. The strongest association to water quality was salinity.

Other studies mentioned earlier include Lanois and Green (2011), who applied the "flushing rate" adjustment to AHOD calculations, and Miller (2010), who noted the impact of drawdown on HOD estimates.

Welch et al. (2015) discussed the effect of flow and residence time on DO levels in Lake Spokane. The researchers found that higher residence time and lower flows are associated with lower minimum DO levels. The effect of flow has been particularly evident in the most recent decade after significant decreases in TP loading to the lake reduced the relative impact of nutrient inputs. Similar patterns were described in Avista's 5-year assessment (Avista, 2017).

Structural and operational factors

Understanding the structure and operation of a dam and reservoir is critical to understanding DO dynamics in the reservoir. How the reservoir is managed can increase the variability of DO conditions and introduce additional complexity to accomplishing representative monitoring and calibrating a model. At the same time, the ability to manipulate the reservoir could introduce management options to improve DO that might not be available for an unregulated lake.

Reservoirs differ from lakes in a variety of ways, but key factors are structural and operational (Thornton, et al., 1990; Jørgensen et al., 2005).

- While lakes typically have a natural outlet control with a surface overflow, reservoirs are controlled by a dam which has been designed with outlets that may include releases from the surface, mid-level, deep, or some combination.
- While lake levels are generally controlled by a balance between inflows and the outlet control, dams often control lake levels as part of their management objectives. In many cases this can involve wide ranges between full pool and drawdown that can occur daily, over several weeks, seasonally, and on an annual basis.
- As a result of how dam releases are managed, reservoir residence times and flushing rates may vary widely.
- The combination of outlet depth, release rates, and elevation changes can have significant effects on the stratification structure and velocity profiles of the reservoir.

Taylor and Golla (2006) examined the effect of drawdown on the longitudinal structure of the Lake Lewisville reservoir in Texas. The locations of riverine, transition, and lacustrine zones shift as reservoir levels drop. As a result, water quality targets and compliance points may also change spatially with reservoir elevation changes. This case study illustrates how the reservoir elevation is driven both by drought conditions, which in this case reduced available storage on an annual basis, and by water supply releases from the reservoir, which have a seasonal pattern repeated every year.

The study of Elephant Butte Reservoir (on the Rio Grande in New Mexico; Canavan and Davis, 2005) noted that extreme drawdown, because of hypolimnetic withdrawals, disrupted stratification and favored eutrophic conditions.

The study by Hudson and Vandergucht (2015) described above noted the effect high inflows on allochthonous loading on DO in Lake Diefenbaker (LD). In addition, they note:

> *…mid-depth withdrawal from reservoirs (as in LD) hastens the movement of this low DO water down the length of the reservoir forming a widespread metalimnetic oxygen minimum…In fact, the metalimnetic DO minimum in LD was evident throughout the reservoir … in July and August…*

A key element of water quality modeling in reservoirs is being able to reproduce these structural and operational factors in the model. This is necessary to accurately simulate the physical characteristics of the reservoir (such as stratification depths and volumes and velocity profiles). It also allows for simulations of climate and hydrology variability interacting with dam operations, or of alterations of the dam structure or operational rules.

The East Canyon Reservoir model (Miller, 2010) had several challenges with modeling the hydraulics of the dam and reservoir. The existing dam includes surface and low elevation outlets, but it also inundated two previous dams. These previous dams had breaches in the hypolimnion, intended to offset the "skimming" effect of surface waters being forced over the tops of the submerged dams. The complexity that the basins and barriers created were included in the simulation, and appeared to perform well.

East Canyon Reservoir has hydraulic characteristics that interact with flow and weather conditions in unique ways. For example:

- Prevailing winds, depending on their direction, can move floating blue-green blooms away from the dam, redistributing it into other parts of the reservoir, or towards the dam, where it can be entrained into the dam outlet flow.
- Extensive drawdown can expose the sidewalls of the reservoir, which tend to be barren of vegetation but holding deposited organic matter. Sediment scour generated by overland flow down the sidewalls can introduce a sudden release of allochthonous input, which W2 currently models inadequately.
- Low levels of outlet flow created unique downstream conditions that W2 modeled poorly. There appeared to be groundwater and dam seepage flows that had different chemical dynamics (phosphorus adsorption and transport) that had not been adequately characterized.

The Lake Spokane DO TMDL model addressed the dam's structure and operations. The model includes a mid-level outlet at the dam and observed outflows. Calibration included matching observed and modeled lake water levels (Berger et al., 2009), which captured the fall drawdown and spring refill (a part of normal dam operations). Wells and Berger (2016) notes the effect of the outflow level on temperature, water age, and velocity as simulated by the model.

Climate change impacts

Climate change will be adding additional complexity to the interactions of lake and reservoir ecosystems. Adrian et al. (2009) provide an overview of limnological variables that are likely to be sensitive to drivers affected by climate change:

- Hydrology: the inflow characteristics related to snow shifting to rain, storm intensity, and inflow timing
- Water temperatures: increased epilimnetic temperature, duration of stratification, and depth of the thermocline
- Ice phenology: frequency and length of lake surface freezing, and timing of melt-out
- Transparency: shifts in patterns of turbidity and Secchi depth
- Water chemistry: increasing hypolimnetic DO deficits; conductivity, pH, or alkalinity shifts
- Community structure: shifts in trophic state from shifts in nutrient loading, stratification, and water temperatures; shifts in composition and timing of algal taxa and fish species;

Concerning the last point, the impacts of increasing CO_2 levels and a changing climate will only add to the ecological complexity of phytoplankton dynamics. An example of research into this question is a review of research by Paerl and Huisman (2009), who found that:

> *…regional and global climatic change may benefit various species of harmful cyanobacteria by increasing their growth rates, dominance, persistence, geographic distributions and activity. Future climatic change scenarios predict rising temperatures, enhanced vertical stratification of aquatic ecosystems, and alterations in seasonal and interannual weather patterns (including droughts, storms, floods); these changes all favour harmful cyanobacterial blooms in eutrophic waters.*

There is some evidence that a direct effect may occur from rising atmospheric CO_2 levels. Ji et al. (2017) studied the effect of elevated CO_2 on competing green algae and cyanobacteria. They evaluated a resource competition model for phytoplankton species that include carbon speciation, pH, and light. They found that low CO_2 levels favored green algae while "bloom-forming cyanobacteria with high-flux bicarbonate uptake systems will benefit from elevated CO_2 concentrations." One of their conclusions was that "a mathematical model can quantitatively predict dynamic changes in phytoplankton species composition, carbon speciation, pH, alkalinity and light during the competition process."

Reichwaldt and Ghadouani (2012) evaluated the effect of future changes in rainfall patterns on cyanobacteria blooms. Increased frequency and intensity of rainfall has been predicted by climate models, which could reduce blue-green populations through increased dilution and flushing. However, it could also increase the runoff of nutrients, which could favor increased blue-green blooms. Under hydrologic conditions at the other extreme, long dry periods or droughts could be favorable to cyanobacteria blooms by promoting warmer water temperatures, more stable water column stratification, and increased eutrophication.

Marcé et al. (2010) studied Sau Reservoir in Spain to evaluate the effect of El Niño Southern Oscillation (ENSO) climate cycles on flow and water quality, and the effect of decreasing streamflow trends on anoxia. They applied a spectral analysis to ENSO and found a relationship between ENSO cycles and streamflow. Overall, climate influences were producing a decreasing streamflow trend, which in turn was the principal driver for increasing levels of the Anoxic Factor in the reservoir. This effect was particularly evident in dry years. The effect on water quality was that "the streamflow trend prevented ~40% of the potential improvement in oxygen levels due to remediation measures."

In general, assessment of recovery will be complicated by long-term trends in drivers such as air temperatures and inflow hydrology. Researchers using Global Climate Models have downscaled their results to the Pacific Northwest. Projections for the rest of this century are indicating an ongoing shift towards hotter, drier summers and winters that are wetter and relatively warmer.

These patterns were observed by Avista (2017) in their 5-year assessment of Lake Spokane water quality. Air temperatures from the Spokane International Airport have increased by about 1°C over the last 50 years. Comparing conditions found in 1972-1985 to 2010-2016 conditions, water temperatures in the lake have increased by about 1°C.

Tools are becoming increasingly available for evaluating future changes. The University of Idaho has created the Northwest Climate Toolbox[5] from which site-specific future scenarios can be obtained. For example, specific impacts on Lake Spokane could include:

- Increased summer temperatures with more intense heat waves, causing and longer periods of stratification. (Figure 15)
- Increased precipitation will likely lead to increased stormwater, erosion, and wash-off of pollutants. (Figure 16)

Assessments of recovery that include evaluating trends in reservoir limnological metrics will also have to take into account the effect of long-term climate trends.

Figure 15. Maximum temperature projections for Spokane, WA from the MACA climate dataset.

Figure 16. March-May precipitation projections for Spokane, WA from the MACA climate data set.

[5] https://climatetoolbox.org/tool/Future-Climate

Indicators, criteria, and multiparameter assessments

Although the individual elements of a reservoir's ecosystem can each be studied in detail, there are also some benefits to having multi-dimensional tools that look at ecosystem health more holistically. In addition, having criteria or indicators that can be applied and compared across multiple lake systems helps to provide some context and standard for understanding reservoir health.

EPA National Lakes Assessment

Every five years, the U.S. Environmental Protection Agency (EPA) monitors a suite of water quality indicators as part of the National Lakes Assessment (NLA). The last report presented results from 2012 (U.S. EPA Office of Water, 2016). The EPA describes the 2012 NLA as:

…a second evaluation of the biological, chemical, physical, and recreational condition of lakes in the United States, the first having been conducted in 2007. During spring and summer of 2012, 89 field crews sampled 1,038 lakes across the country. Each field crew used consistent procedures to sample benthic macroinvertebrates (e.g., insect larvae, snails, and clams), zooplankton (small animals in the water column), algal toxins, atrazine, and nutrients and to observe near-shore habitat so that results could be compared across the country. These measured values were compared to NLA benchmarks, which are points of reference used to determine the proportion of lakes that are relatively high quality (least disturbed), medium quality (moderately disturbed), and degraded (most disturbed) in condition.

The NLA is based on a probabilistic design, and includes some reservoirs.

Table 4 lists the indicators evaluated in the NLA. This nation-wide assessment provides an opportunity to collect some of these parameters as part of the DO TMDL 10-year assessment. The benefits could include:

- Following a nationally established set of protocols for monitoring (U.S. EPA, Office of Water, 2012)
- Comparison of observed values to a national database and set of benchmarks.
- Statistical analysis of observed data in comparison to a national data set. Yuan and Pollard (2015) provide an example of the kind of analysis that is possible.

Table 4. Indicators evaluated in 2012 National Lakes Assessment.

Biological	Chemical	Physical	Recreational/ Human Health
• Benthic macroinvertebrates • Chlorophyll a • Zooplankton	• Acidification • Dissolved oxygen • Nitrogen • Phosphorus • Trophic state	• Drawdown exposure • Lakeshore disturbance • Lakeshore habitat complexity • Riparian vegetation cover • Shallow water habitat	• Algal toxin (microcystin) • Cyanobacteria • Mercury • Atrazine

Although not a replacement for regulatory criteria, the NLA could provide a reference data set for comparison that could help create some context for restoration of Lake Spokane.

Other criteria and indicators

Kennedy and Thornton (2001) described a conceptual framework for reservoir water quality indicators. Working with a panel of reservoir personnel at a national conference they presented a suite of example indicators, which included 15 water quality and biological parameters. They acknowledged the value of categorizing indicators by ecoregions. In their conclusions, they make several pertinent observations:

When properly applied, environmental indicators provide valuable insight to complex environmental problems and can be used to effectively support the management and decision-making process. However, indicators are often based on limited data and prudent choices must be made in their selection, application and interpretation. Managers must insure that indicators are relevant to management issues and target appropriate attributes of the environment.

Kennedy (2001) explores ways of categorizing reservoirs for setting nutrient criteria. Key factors identified include:

- Location in the drainage basin. Reservoir characteristics differ widely depending on their location, for example: differences between upland tributary reservoirs, mainstem storage reservoirs, and mainstem run-of-the-river reservoirs.

- Dam structure and operation. The interaction of reservoir depth, withdrawal depth, volume released, and thermal structure of the water column all affect the temperature structure and trophic responses to nutrients.

- Hydraulic retention time. Reservoirs vary widely in retention time (1 day to several years). This can affect material retention rates, thermal structure, and size and composition of planktonic communities.

- Characteristics of sediment and nutrient retention.

- Analytical tools Kennedy recommended include frequency distribution and water quality models.

This analysis highlights the many factors that affect a reservoir and its trophic status, and the sources of variability among reservoirs that make comparison challenging.

EPA published water quality recommendations for supporting nutrient criteria in lakes and reservoirs. The two relevant to Lake Spokane are documents addressing "Ecoregion II" – the Western Forested Mountains (U.S. EPA Office of Water, 2000), and "Ecoregion III" – the Xeric West (U.S. EPA Office of Water, 2001). The headwaters of the Spokane River are in the Western Mountains (Northern Rockies) Ecoregion, and in Washington the river serves as a boundary between Northern Rockies to the north and the Xeric West (Columbia Plateau) Ecoregion to the south. The main value of these documents are the reference conditions it provides for nutrients, chlorophyll-*a*, and Secchi depth in each Ecoregion.

Vaga et al. (2006) authored an EPA report on classifying reservoirs in the Pacific Northwest (Washington, Oregon, and Idaho) for nutrient processing. Twenty reservoirs were sampled from the Western Forested Mountains Ecoregion, and twenty-seven from the Xeric West Ecoregion. Statistical analyses applied included two-way analysis of variance, Spearman correlation coefficient, and principle components analysis. No categories were identified for Western Forested Mountains. Three categories were proposed for the Xeric West:

- Category 1 – Low ionic strength, high transparency, low absorbance, low turbidity, low chlorophyll.
- Category 2 – Moderate ionic strength, moderate transparency, moderate absorbance, moderate turbidity due either to algae or particulate matter.
- Category 3 – High ionic strength, very high absorbance, very low transparency due to algal and/or non-algal turbidity.

Reference values are reported for nutrients, Secchi depth, and chlorophyll-*a* for each category.

European Union Water Framework Directive

The European Union in 2000 issued a Directive "establishing a framework for Community action in the field of water policy". The Water Framework Directive resulted in a variety of implementation strategy guidance documents, two of which are relevant to this study:

- Guidance Document No. 10: Rivers and Lakes – Typology, Reference Conditions and Classification Systems (European Communities, 2003)
- Guidance Document No. 23: Guidance Document on Eutrophication Assessment in the Context of European Water Policies (European Communities, 2009)

Guidance Document No. 10 presents five classifications of ecological status based on comparison to reference conditions ("undisturbed conditions"): bad, poor, moderate, good, and the reference conditions themselves. A list of quality elements are provided for assessment of ecological status of lakes:

- Biological Elements
  o Composition, abundance and biomass of phytoplankton
  o Composition and abundance of other aquatic flora
  o Composition and abundance of benthic invertebrate fauna
  o Composition, abundance and age structure of fish fauna

- Hydromorphological elements supporting the biological elements
  o Quantity and dynamics of water flow
  o Residence time
  o Connection to an aquifer
  o Lake depth variation
  o Quantity, structure and substrate of the lake bed
  o Structure of the lake shore

- Chemical and physiochemical elements supporting the biological elements
  o Transparency
  o Thermal conditions

- o Oxygenation conditions
- o Salinity
- o Acidification status
- o Nutrient conditions
- o Specific pollutants

For each of these elements, a table of detailed assessment criteria are provided for determining the ecological status classification. Anthropogenic "pressures" are also described that can impact each of these elements, which include: pollution, morphological alterations, water withdrawals, flow regulation, alien species, fisheries, and recreation.

Guidance Document No. 23 provides guidance on ecological assessment for eutrophication of waters. A checklist for features of eutrophication is provided, which includes factors related to lakes:

- Causative factors:
  - o Riverine, direct, and atmospheric inputs of nutrients (P, N, Si)
  - o Internal nutrient loading

- Supporting environmental factors:
  - o Light availability (irradiance, turbidity, suspended load)
  - o Hydrodynamic conditions – stratification, flushing, retention time
  - o Climatic/weather conditions (wind, temperature)
  - o Typology factors: alkalinity, color, size, depth, share of area shallower than the stratification layer
  - o Other pressures (toxic substances, hydromorphological pressures)
  - o Zooplankton grazing (top-down control)

- Direct effects of nutrient enrichment:
  - o Phytoplankton
    - Increased biomass (e.g. chlorophyll a, organic carbon and cell numbers)
    - Increased frequency and duration of blooms
    - Increased annual primary production
    - Shifts in species composition to higher proportion of potentially harmful or toxic species (from chrysophytes and diatoms to cyanobacteria and chlorophytes)
  - o Macrophytes including macroalgae
    - Increased biomass
    - Shifts in species composition
    - Reduced depth distribution consequent shift in balance of species

- Indirect effects of nutrient enrichment
  - o Organic carbon/organic matter
    - Increased organic carbon concentrations in water and sediment
  - o Oxygen
    - Decreased concentrations and saturation percentage
    - Increased frequency of low oxygen concentrations
    - Increased consumption rate
    - More extreme diurnal variation in surface waters (oversaturation at day and undersaturation at night)

- - Reduction in hypolimnion during stratification periods
    - Occurrence of anoxic zones at the sediment surface ("black spots")
  - Fish
    - Changes in abundance
    - Changes in species composition
    - Mortalities resulting from low oxygen concentrations
  - Benthic invertebrates
    - Changes in abundance and biomass
    - Changes in species composition
    - Mortalities resulting from low oxygen concentrations
  - pH increase in surface waters
  - Internal loading of phosphorus
  - Increased ammonia concentration in bottom waters
  - Often changed top-down control due to changed predation on zooplankton
  - Release of soluble Fe, Mn from sediments
- Other possible effects of nutrient enrichment
  - Bad smell, turbid waters
  - Incidence of toxic algal blooms increases
  - Loss of visual amenity due to color in water

The intent of presenting the EU Water Framework Directive here is not to suggest that the entire framework be applied, which would be impractical and of limited value. However, this information is helpful in providing an overview of the complexity of lake ecosystems and the structured approach taken to assess their quality. This approach is holistic and multi-dimensional, and attempts to address a wide range of pressures and impacts. In that sense this information can be helpful as a conceptual framework for organizing a comprehensive assessment strategy.

Toolkits

Although the term "toolkit" has become somewhat cliché, it does capture a concept of integrating a variety of methods for an overarching objective. Two articles suggest a structured approach to developing an assessment toolkit.

Holland et al. (2003) explain that a toolkit can provide integrated information that increases productivity and acceptance. It needs to be designed with the users' needs and skills in mind. Issues to consider include: web integration, interoperability, conceptualization, collaboration, and integration of science into decision-making. They provide a detailed description of the toolkit development process.

Bartell (2003) explains that a toolkit can either be a collection of models or an integrated model system. Important questions for toolkit development include:
- What categories are desired?
- What are the criteria for including tools?
  - Examples of criteria: realism, relevance, flexibility, uncertainty analysis, scientific and regulatory acceptance, parameters, quality of results, resources needed
- How will the toolkit meet project objectives?

- How will the toolkit be useful to users?
- Who manages the toolkit?
- How will data be managed?

An integrated toolkit system is more challenging and requires the assessment of integration methodology. However, the same development process can be applied to a toolkit that includes a variety of methods which are integrated qualitatively.

Trends and recovery rates

One of the objectives of this study is to "analyze and evaluate the identified literature in terms of … the ability of methods to characterize trends and rates of recovery." Virtually all of the methods discussed in this literature review lend themselves to some sort of trend or recovery assessment. These methods will be discussed under general categories of the statistical analysis of data, and analysis with models.

Statistical methods

Significant trends or recovery can be evaluated by several general categories of methods:
- Time series trends: a long-term time series spanning a recovery period can be assessed with a variety of parametric or nonparametric methods. The most common parametric method is a linear regression versus time. A common nonparametric method is the Mann-Kendall test. A nonparametric smoothed regression line can be created with the LOWESS method (locally weighted scatterplot smoothing). Parametric methods have a variety of assumptions that need to be evaluated (such as normality, homoscedasticity, independence), but can provide more information about the trend.

- "Step" tests: two datasets separated in time can be evaluated by comparing whether a significant difference exists between the data sets. The 't' test is often applied to compare the means of two data sets. The specific method may vary by the context and assumptions that apply to the data sets, such as independence or normal distribution. Other parametric methods include the Pearson correlation of one-way analysis of variance. Nonparametric tests include the Mann-Whitney U test, Spearman correlation, or the Kruskal Wallis test. Nonparametric methods have the advantage of not assuming normal distribution.

- Change points and regime shifts: as noted in earlier discussions, the shift in ecosystem structure may lag behind the shift in drivers. Therefore, before a step test can be applied, the change point for that regime shift needs to be determined. Anderson et al. (2015) reviews some of the methods for detecting a change point. Toms and Lesperance (2003) present the piecewise regression technique for modeling systems that pass a breakpoint or threshold into a different regime.

- Multivariate statistics: more complex statistical methods, such as regression trees or multiple linear regressions, can evaluate the interdependency of the variables being measured in relation to any changes in DO. Ordination techniques can also be used to show significant changes in the biological communities over time, such as for phytoplankton species assemblages.

A powerful tool for statistical analysis is the open source software 'R'. A variety of packages have been developed that are directly applicable to limnological analysis.[6]

The categories of approaches discussed above can be evaluated for statistical methods to assess progress towards recovery. In the sections that follow, the approaches discussed above are rated "high", "medium", or "low". This prioritization is based on the ease of use (time and resources need for its use) and applicability (relevance of the information for Lake Spokane). Some examples found in the literature review are included. These priorities are provided as a preliminary screening – before methods are selected and implemented, more analyses should conducted of the power of tests and the data needed to find significant relationships.

Dissolved oxygen dynamics

- High: The anoxic factor (AF) or hypolimnetic oxygen depletion (AHOD or VHOD) can be compared either with trend or step tools. The methods employ simple calculations and are robust in terms of reducing short-term variability and capturing inter-annual changes.
  - Examples: Lehmann, 1988; Nurnberg, 1995; Stevens, 2003; Matthews and Effler, 2006; De Lanois and Green, 2011
- Medium:
  - Water column DO demand, or the percent change in a median or low percentile value (trend or step).
  - The length of the anoxic season (trend or step) if adequate data are available.
  - Cumulative frequency distributions or cumulative volume method over two time periods (step).
  - Depth- or volume-weighted average DO values (trend). However, the averaging method introduces uncertainty and needs to be consistent.
  - The hypoxic factor (HF), percent time below a threshold, or volume or depth below a threshold (trend or step) – requires a specific threshold for comparison.
    - Examples: PSOMAS, 2002; IDEQ and ODEQ, 2004
- Low:
  - Time of anoxia onset (trend or step) – variable metric, less robust

Trophic status

- High: Remote sensing tools for assessing chlorophyll-*a* from satellite data provide a long-term data set that can be powerful for detecting trends. Data analysis can be resource intensive.
  - Example: Hansen et al., 2015.
- Medium:
  - The Carlson TSI is a classic method and easily communicated (trend or step). However, large data sets may be needed to obtain sufficient sensitivity for trend detection, and results of the different factors may be ambiguous or contradictory.
  - Relationships between DO and trophic factors (such as phosphorus and chlorophyll-*a*) can be analyzed (trend or step), and could reveal shifting relationships. However, this

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[6] For example: EGRET and streamMetabolizer (https://owi.usgs.gov/R/); rLakeAnalyzer (https://www.rdocumentation.org/packages/rLakeAnalyzer/versions/1.11.0); Analogue (https://www.fromthebottomoftheheap.net/code/r-packages/analogue/).

might require a large and consistent data set to obtain secondary information. Also, the relationships would be statistical, and therefore unable to reveal causative mechanisms.

Primary production

- Medium: Diel data analysis from continuous DO monitoring (such as the Delta Method) can be analyzed from data that is relatively simple to collect (trend or step). However, spatial and temporal variability would need to be considered.
- Low: Isotope methods could be analyzed in theory, but they are resource intensive and therefore it is difficult to collect sufficient data to detect significant temporal patterns from other sources of variability.

Sediment

- Medium: Sediment cores are a composited time series. As such, they are a direct and powerful way to see changes over time by evaluating the sediment layers (trend or step). However, the method is resource intensive and may provide results that are difficult to resolve into quantifiable trends.
- Low: SOD and nutrient release rates could be analyzed for changes over time (step), but the methods are resource intensive and it would be difficult to get sufficient data for a statistically valid comparison that detects temporal changes amidst the noise of spatial variability.

Phytoplankton

- Medium: Algal community composition can be evaluated over time with step trends, regression slopes, or ordination methods[7]. However, the amount of information needed to determine significant change makes this a difficult approach.

Fish

- Medium: The temperature-DO squeeze can be quantified as volume within optimal thresholds and assessed over time (step or trend). However, results would depend on how thresholds are defined, and could be influenced by climate or hydrology trends.

Climate, hydrology, operations

- High: Although not recovery in itself, trends in climate, hydrology, or operations should be analyzed as part of the assessment of any other parameter (trend or step). This allows trends driven by nutrient loading to be separated from trends in these external forcing factors.

Criteria and indicators

- Medium: Analyzing changes in parameters as compared to EPA Lakes Assessment values could provide a useful benchmark for progress (step).

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[7] For example, the R package "Vegan" (https://cran.r-project.org/web/packages/vegan/vignettes/intro-vegan.pdf)

Modeling methods

The review of literature has found that the CE-QUAL-W2 model is widely used for the analysis of water quality in reservoirs. Many of the tools for data analysis reviewed in this study can be applied either to monitoring data or modeling results. The existing model is a valuable tool for additional analyses of recovery. In addition, as basis of the TMDL, it is a critical element of understanding progress in the TMDL.

For assessing recovery, running the model for conditions during the 10-year assessment provides an opportunity to compare results to the previous model. In this context, modeling can have several purposes:

- Assess changes in a parameter that is more easily modeled than monitored, with a data set calibrated to observed data and expanded by the model.
- Assess the understanding of how the ecosystem functions and how ecosystem functions are changing over time by replicating processes with the model.
- Compare past and present conditions under critical or extreme events (e.g. high temperatures or low flows) for which there are data gaps.
- Simulate future changes based on historic and current patterns.

Two approaches could be considered for use of the existing Lake Spokane W2 model:

- Use the existing model with a new data set collected as part of the 10-year assessment. This would be a relatively simple approach and allow comparisons with the same calibrated model. The downside might be the missed opportunity for model improvements.
- Update the model with existing enhancements or with the addition of new capabilities. The benefit of this approach is an improved model that includes features which better reproduce conditions in the reservoir and capture possible ecosystem shifts. The downside of this approach is that this would be require a significant investment of resources for possibly a small increase in useful information.

Water quality models can be run as long-term simulations to better assess future conditions (for example: Miller, 2010). These long-term simulations can link past data to present and then project into the future. Alternatively, model runs for historic blocks of time can be compared to current simulations in a step fashion. This approach may be more desirable if there have been shifts in ecosystem components or kinetics, such as algal species shifts. Sensitivity analysis can evaluate model functions to shed light on key ecosystem features.

Fish bioenergetics and volitional movement models provide a tool to assess the fishery response to changing environmental factors. Based on calibration data sets, a longer data set of fish response can be developed. Data gaps for critical years can be evaluated with the model, and the model time series (or two modeled periods) evaluated for changes.

Graphical methods

In many cases, qualitative methods can provide information on system changes. Graphical presentations can reveal and communicate data patterns. Examples of this include:

- A time series plot with a scatter plot or bar chart (PSOMAS, 2002; Figure 17)
- Multiple time series showing changes of several parameters, such as algal assemblages (Edmondson et al., 1982; Figure 18)
- Fitting a LOWESS regression curve to a time series of data (Stevens, 2003; Figure 19).
- Combined time series graphs of varying formats (Edmondson et al., 1982; Figure 20)
- GIS-based heat maps showing changes between two time periods (Hansen et al., 2015; Figure 21)
- Isopleths or heat maps of DO by depth over time (Nürnberg, 2004; Figure 22)
- X-Y plots with years grouped (Avista, 2017; Figure 23)

Figure 17. Deer Creek Reservoir Average Trophic State Index (TSI) 1981-1999. From: PSOMAS, 2002.

Figure 19. Population densities of prominent species of zooplankton from the top 10 meters in Lake Washington. From Edmondson et al., 1982.

Figure 18. Temporal variations in dissolved oxygen measurements at Carter Lake, sampled near the bottom. From Stevens, 2003.

Figure 20. Above – mean and summer Secchi disk transparency for each year (means for 1971-1975 and 1976-1979 are shown). From Edmondson et al., 1982.

Middle – schedule of diversion of sewage effluent; Line shows relative input of effluent. Bottom – loading rate of dissolved phosphorus; amount contained in sewage effluent indicated by shading.

Figure 21. Estimated chlorophyll distribution in Jordanelle Reservoir, Utah, on 22 August 2002 (left) and 21 May 2003 (right). From Hansen et al., 2015.

Figure 22. DO isopleths in Brownlee Reservoir for 1999 and 2000 near the dam in the lacustrine section. From Nürnberg, 2004.

Figure 23. June-October Volume-Weighted Mean Inflow TP Concentrations related to Minimum Volume-Weighted Hypolimnetic DO Concentrations. From Avista (2017).

Discussion and Recommendations

The ecology of reservoirs and lakes is a highly studied topic. This literature review identified over a hundred articles despite attempting to keep a narrow focus to the objectives of this study. To organize this material, subject areas are proposed that align roughly with the elements of a lacustrine ecosystem that interact with dissolved oxygen, as was presented above and illustrated in Figure 2.

A wide range of information has been presented to provide a comprehensive overview of issues and potential methods related to DO in reservoirs like Lake Spokane. Those results are organized, prioritized, and presented below with the goal of supporting the DO TMDL 10-year assessment. These recommendations represent the professional views of the author, and are intended to stimulate further discussion, planning, and decision-making by staff from Ecology and local partners.

Table A-1 provides a summary of the findings from this review. For each method, information is provided for reference:
- Category: aligns with the section headings
- Purpose: a general description of the principal use of the method
- Contexts: the kind of study for which the method was used and reported.
- Recovery Assessment: how the method could be used to assess change in the reservoir ecosystem
- Case Study Locations: the geographical location of the studies where the method was used
- Useful to Lake Spokane: a prioritization and brief description of how the method might be used.
- Citations: these numbers correspond to the articles listed in the References section

As part of scoping this review, there was interest expressed in case studies that closely resemble Lake Spokane. After reviewing dozens of case studies, my conclusion is that every reservoir represents a unique situation, since they are driven by the many factors discussed above, such as morphology, hydrology, climate, geology, pollution sources, and watershed size and land uses. However, the principles of limnology are transferable across a diverse array of situations, and although the unique characteristics may vary, the methods reviewed are applicable to any medium sized, deep reservoir in a temperate climate, such as Lake Spokane.

Recommendations are provided below, listed by suggested priority (high and medium – methods not reported can be considered low priority), and organized by general categories of opportunity and purpose.

Analyses with existing data

Avista has supported ongoing monitoring of Lake Spokane as part of its FERC license. This has produced a rich database of information. Several of the methods found in the literature review are already being applied or could be added as additional analyses of existing data.

High

- Continue seasonal monitoring, and calculate the annual AHOD, volume-weighted hypolimnetic DO, and AF. Consider using the flushing rate adjustment presented by De Lanois and Green (2011).
- Explore relationships between DO, phosphorus, chlorophyll-*a* and other trophic parameters,.
- Continue to explore methods to calculate the temperature-DO squeeze over the course of each season and over the years that data are available. Develop consistent, agreed-upon methodology for DO and temperature thresholds used in the analysis.
- Use statistical methods to evaluate the effect of seasonal flows and reservoir residence times on hypolimnetic DO levels.

Medium

- Calculate epilimnetic and hypolimnetic volume-weighted average DO for each survey. Consider presenting as box-and-whisker plots with max/min, 25/75 percentile, and median. Follow a consistent methodology through a collaborative process.

Supplementing ongoing monitoring

An additional method could be added to the existing survey design that would provide useful information at a reasonable additional investment in resources.

High

- During surveys, deploy data-logging multiparameter meters to record temperature, DO, and pH from mid-epilimnion at survey stations. Follow the recommendations of Staehr et al. (2010) to optimize representative monitoring. Analyze data for estimates of lake metabolism
- Consider long-term deployment of vertical strings of small temperature and DO data-logging meters, such as HOBO data loggers. Deployment of a water quality profiling buoy might also be considered.
- Continue studying groundwater inflow rates and pollutant loading.
- Review monitoring methods for phytoplankton dominant species and seasonal succession
  - Enhanced monitoring of algal populations and kinetics to support trend analysis and modeling needs.

Recovery assessment studies

Several years of special studies and data collection are expected as part of the 10-year assessment. Methods to assess progress on improving dissolved oxygen and the overall health of Lake Spokane are of special interest.

High

- Conduct intensive monitoring studies to develop data sets that align with past data collection for assessing change over time. Monitoring should be designed to capture spatial and temporal variability to maximum extent possible given available resources.

- Conduct a statistical analysis of limnological parameters for significant trends or changes. These parameters could include: AHOD, AF, temperature-DO squeeze metrics, phytoplankton assemblages, volume-weighted average hypolimnetic DO, and Trophic State Index (TSI).
- Conduct a statistical analysis of the influence of climate, hydrology, and operations on trends in limnological parameters.
- Use box-and-whisker plots, isopleth heat maps, LOWESS smoothed regression lines, and other graphical tools to present change in limnological parameters over time.
- Collect data that aligns with reference sites from comparable reservoirs. This could include monitoring EPA lake assessment indicators and comparing results to data from reference locations.
- To support modeling of current conditions:
  o Design intensive monitoring surveys to collect a comprehensive data set of chemical parameters and flows to meet the needs of the model.
  o Collect local meteorological data for parameters such as wind and air temperature to support updated estimates of reaeration and evaporation.
  o Consider use of the Cumulative Volume Method to compare past and current model scenarios.

Medium
- Compare current and historical data using cumulative frequency distributions
- Conduct a remote sensing study for chlorophyll-*a* using satellite data. To ensure that sufficient data is available to predict chlorophyll-*a* from remote sensing data: collect historical data, and design a special survey to develop a more complete data set of current conditions for one season.
- Conduct a sediment core study. Collect a set of cores, and date and analyze the stratigraphy for historical patterns in key parameters related to DO and eutrophication. This could include: sediment chemistry; carbon and nitrogen isotopes; charcoal; diatom frustules and other fossil phytoplankton indicators; and pigments. Combine the study with a study of SOD and nutrient diagenesis (discussed further below).
- Conduct long-term modeling of fish bioenergetics and volitional movement to determine changes over time.

Special studies of ecosystem functions

Along with being able to assess improvement in the health of Lake Spokane, it's also important to understand how the lake ecosystem functions. This helps to determine how restoration actions have affected the lake and to ensure that future actions are appropriately targeted. It also helps to identify critical features of the lake that can be better simulated if model enhancements are desired.

Given the complexity of a lake ecosystem, this knowledge is never complete. Key studies can fill data gaps, bring greater focus to understanding of lake health, and provide a baseline for future assessments. Several studies and data collection efforts are recommended that can be useful to a better understanding of Lake Spokane ecology:

High

- Conduct intensive monitoring surveys that include limnological parameters that provide detailed information regarding ecological functions.
- Conduct spatially and temporally intensive surveys with data-logging multiparameter meters to better assess lake productivity using diel oxygen methods. Following the recommendations of Staehr et al. (2010) and Van de Bogert et al. (2007), assess differences in productivity estimates with depth, in littoral areas, and in the riverine and transition zones. This will better determine the spatial and temporal variability of productivity and assess how well mid-lake, mid-epilimnion measurements represent whole lake productivity.
- Conduct a sediment diagenesis study, which includes the collection of core samples and incubation in the lab with measurements of SOD, TOC content, TP content and release rates, and Fe/Mn chemistry.

Medium

- Conduct a multivariate statistical analysis of limnological data to improve understanding of how parameters interact, how relationships may indicate the key drivers for DO, and how interacting parameters may be changing over time.
- Conduct an ^{18}O diel isotope study to complement the diel DO studies and provide better estimates of the temporal variability of productivity and respiration in the lake.
- Develop a fish bioenergetics and volitional movement model that links lake productivity to fish populations, growth, and behavior.
- Assess ways to better simulate productivity and nutrient/carbon dynamics in the riverine and littoral zones where they differ from lacustrine conditions and significantly affect model results. This information can be used either for a stand-alone analysis or for model enhancements.
  - Data needs: mapping of littoral and riverine areas shallow enough to support periphyton or aquatic plants, to better quantify depths and volumes and assess the productivity and nutrient/carbon dynamics of these areas.
- If model enhancements are planned:
  - Assess ways to better simulate multiple algal groups, possibly including more algal groups, improved algal kinetics, or the enhancements developed for East Canyon Reservoir (Miller, 2010).
  - Develop improved algorithms for predicting SOD and nutrient release over time from water column conditions, settling rates, and sediment physical and chemical properties.

Using this information

Sifting through the choices

The purpose of this review was to "to identify and evaluate alternative methods or analyses…" The next step is to conduct a collaborative process to evaluate the findings of this review and resources needed, and develop a comprehensive monitoring strategy and plan. Recovery may take decades, and the value of long-term efforts that address ecosystem processes has been noted by researchers (e.g. Schindler, 2012).

To make sense of this complex collection of information and put it to use in Lake Spokane, a step-wise approach could be helpful:

- Develop questions about Lake Spokane dissolved oxygen conditions and ecosystem that stakeholders would like answers to.
- Develop objectives for monitoring, modeling, and other analysis to support the 10-year assessment
- Identify data and information needs that align with assessment objectives
- Scope potential studies and monitoring programs for resource needs (time, staff, and funding)
- Prioritize studies and monitoring and organize into a structure that aligns with objectives, opportunities, and timelines.

The "toolkit" approach should be considered as a way to organize monitoring during the 10-year assessment.

Key points

A few key points are offered as results from this analysis:

- Evaluation of recovery could make use of both modeling and monitoring.
  - Collecting additional monitoring data and conducting other special studies can support additional analysis to increase understanding of the Lake Spokane ecosystem and the recovery trajectory.
  - Modeling can help identify progress, assess ecosystem interactions, and project to conditions that cannot be monitored.
    - The existing model could be run to evaluate current conditions with a new monitoring data set.
    - Also, given the potential changes to the lake's ecosystem from nutrient reductions, the improvements in the W2 model since the TMDL was developed, and the potential for additional model enhancements, updating the Lake Spokane W2 model could be considered.
- The tools described in this report fall into two general categories:
  - Methods that help to assess and quantify recovery of the ecosystem in general and of dissolved oxygen conditions specifically.
  - Methods that help increase knowledge of ecosystem processes. This information helps us to understand how the waterbody has changed, which activities will help it to continue to improve, and the overall state of ecosystem health.

Next steps

The information in this report represent my best efforts to find, organize, and present useful ideas. Because of the breadth of the subject, they represent a sampling of limnological knowledge – there are likely more methods available and emerging every day. I offer a wide variety of methods to show the range of available tools, with the understanding that the sources or amounts of potential resources needed are uncertain, and that only a few may ultimately be

chosen. I have provided a few suggestions for priority based on the overall analysis and my understanding of Lake Spokane conditions.

And as noted under *Study Purpose*, determining compliance with water quality standards was not included in the analysis, since it is the responsibility of the Water Quality Program.

This study only represents a first step and are intended to stimulate thought and discussion. This information hopefully serves as a compendium of tools that local stakeholders and Ecology can explore, prioritize, and select from for the 10-year assessment.

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Appendices

Appendix A. Summary table of methods reviewed

Table A-1. Summary of methods reviewed

Method	Category	Purpose	Contexts	Recovery Assessment	Case Study Locations	Useful to Lake Spokane	Citations
General Principles	General	all	academic	n/a		Foundational	6, 7, 21, 25, 40, 44, 50, 108, 112, 129, 130
Water column DO demand (BOD – p. 16)	DO Dynamics	assess processes	TMDL	trend or step	OR	medium - routine method, standard for modeling	31, 37
Hypoxic factor (HF – p. 17)	DO Dynamics	assess impairment	recovery assessment	trend or step	ID	low - useful to assess thresholds	82, 83
Anoxic factor (AF – p. 17)	DO Dynamics	assess impairment	recovery assessment, drinking water	trend or step	Europe, TN, CA	high - can use existing data; good for trends	12, 63, 69, 80, 81, 83
Hypolimnetic Oxygen Depletion (HOD – p. 18)	DO Dynamics	assess impairment	WQ assessment, Recovery assessment, Project impacts, drinking water	trend or step	Sask, NY, TN, AR, OK, CO, CA, W.WA, E.WA	high - can use existing data; used by Welch et al; flushing adjustment by De Lanois; can be used for trends	12, 21, 24, 26, 29, 53, 63, 68, 70, 72, 81, 83, 125, 129, 130
Areal Hypolimnetic Mineralization (AHM – p. 19)	DO Dynamics	assess impairment	recovery assessment	trend or step, compare to reference	Europe	low - complex, little added information	75
% time below a threshold (p. 19)	DO Dynamics	compare to criteria	TMDL	step	UT, ID, OR	low - applicability poor, better tools available	72, 107
% change in median or low percentile (p. 19)	DO Dynamics	assess impairment	Project impacts	trend or step	CO	medium - can use existing data; less useful than other tools, but useful as part of broader assessment	84, 85
Time of anoxia onset (p. 19)	DO Dynamics	assess impairment	WQ assessment	trend or step	MO	low - applicability poor, better tools available	59

Method	Category	Purpose	Contexts	Recovery Assessment	Case Study Locations	Useful to Lake Spokane	Citations
length of anoxic season (p. 19)	DO Dynamics	assess impairment	TMDL	trend or step	CO	medium - can use existing data; less useful than other tools, but useful as part of broader assessment	84
DO time series (p. 19)	DO Dynamics	assess impairment	TMDL	qualitative	MD, UT, OR, W.WA	low - routine method	19, 54, 72, 106
cumulative frequency distribution (% of time – p. 19)	DO Dynamics	assess impairment	TMDL	step	MD	medium - can use existing data; less useful than other tools, but useful as part of broader assessment	54
depth- or volume-weighted average (p. 20)	DO Dynamics	compare to criteria	TMDL, project impacts	trend	CO, ID, E.WA	medium - historical method, needs consistent approach	14, 56, 73, 107, 124, 127
volume or depth anoxic or below a threshold (p. 20)	DO Dynamics	assess impairment	TMDL, WQ assessment, Indicators	trend or step, compare to reference	USA, MO, ID	low - applicability poor, better tools available	54, 55, 59, 90, 132
DO and %DO profile, box plots, isopleths, heat maps (p. 21)	DO Dynamics	assess impairment	TMDL, recovery assessment, Project impacts, drinking water	qualitative	Sask, MD, AK, CO, W.WA, E.WA	medium - some historical use, potentially more; useful for communication	19, 27, 34, 49, 53, 54, 55, 83, 84, 103
Spatial heterogeneity (p. 22)	DO Dynamics	assess metabolism	recovery assessment	step in sensitive areas	Sask, E.WA, W.WA	medium - addresses data gaps	13, 23, 34, 53, 55, 83, 101, 118
cumulative volume analysis (p. 23)	DO Dynamics	compare to criteria	TMDL modeling	step	W.WA	medium - powerful method, but complex	88
TSI (trophic status indices – p. 26)	Trophic state	assess impairment	Trophic status assessment, recovery assessment, TMDL	trend or step	MD, OK, NM, E.WA	medium - classic method, but perhaps not sensitive as trend indicator	16, 17, 24, 54, 65, 81

Method	Category	Purpose	Contexts	Recovery Assessment	Case Study Locations	Useful to Lake Spokane	Citations
Relationships between DO and trophic parameters (p. 26)	Trophic state	assess impairment	TMDL, recovery assessment, drinking water	trend or step	USA, MD, TN, MO, CA, ID, OR, E.WA	medium - relationships may reveal shifting DO drivers	12, 18, 21, 22, 54, 55, 59, 63, 65, 83, 86, 92, 128, 132
Chlorophyll-a remote sensing (p. 29)	Trophic state	assess impairment	Trophic status assessment, TMDL	trend	AZ/NV, WY, UT, OR	high - powerful tool, produces long-term data set	32, 48, 111
diel DO analysis (Delta method – p. 31)	Primary Production	assess metabolism	TMDL, recovery assessment, research	trend or step	Quebec, OR	high - simple to do, useful productivity metric	20, 23, 38, 51, 52 71, 95, 101, 118, 131
O18 isotope diel analysis (p. 35)	Primary Production	assess metabolism	TMDL, recovery assessment, research	n/a	Ontario, IN, OR	low - increase knowledge of lake metabolism; supports modeling; but intensive to implement	51, 87, 89, 109, 119, 120, 121
C14 uptake studies (p. 38)	Primary Production	assess metabolism	academic	n/a		low - support ecosystem understanding, but difficult to do	130
Hypolimnetic CO_2 accumulation (p. 38)	Primary Production	assess metabolism	recovery assessment	step		low - difficult procedure, limited usefulness	129, 130
Sediment respiration & SOD (p. 39)	Sediment	assess SOD	TMDL, recovery assessment, drinking water	step	OK, UT, CA, OR, E.WA	high - data gap, supports modeling	7, 10, 12, 13, 21, 31, 37, 40, 45, 72, 96
Sediment nutrient diagenesis (p. 41)	Sediment	assess processes	Trophic status assessment, TMDL, recovery assessment	step	MD, MI, OK, UT, W.WA, E.WA	high - data gap, support modeling	21, 24, 40, 45, 65, 72, 102, 129
Paleolimnological sediment cores (p. 43)	Sediment	assess ecosystem	Trophic status assessment, recovery assessment	depositional record	Ontario	medium - useful data, requires specialized methods	66, 67, 74, 91, 98, 122, 130

Method	Category	Purpose	Contexts	Recovery Assessment	Case Study Locations	Useful to Lake Spokane	Citations
phytoplankton assemblages (p. 45)	Phytoplankton	assess ecosystem	TMDL, trophic status assessment, recovery assessment, project impacts	qualitative	MD, OK, NM, CO, OR, W.WA	high - important information for ecological health. Already being collected.	15, 24, 33, 37, 54, 57, 68, 72, 84, 85, 86, 94, 96, 99, 100, 123
The temperature-DO squeeze (p. 49)	Fish	assess ecosystem	ESA, Fish, recovery assessment	trend or step, long-term model	CO, UT, ID, W.WA	high - already being done, useful information	4, 8, 11, 30, 39, 46, 58, 59, 64, 77, 104, 123, 125
fish volitional movement (p. 53)	Fish	assess ecosystem	Project impacts	long-term modeling	SC, TN	medium - analyze DO impacts on fish habitat	41, 42, 43, 44, 76, 77, 78, 79
fish bioenergetics (p. 54)	Fish	assess ecosystem	ESA, 401, Fish, recovery assessment, research	long-term modeling	UT, ID, W.WA, E.WA	medium/low - if focus is on fishery and DO secondary	5, 9, 46, 47, 104, 123, 126
Weather, hydrology, and flow conditions (p. 56)	Weather, Hydrology, flow	assess processes	recovery assessment, Project impacts	separate flow and climate effects from recovery, trends	Europe, Sask, TX, CO	high - quantify effects of flow	3, 28, 53, 69, 83, 84, 93
Structural and operational factors (p. 57)	Structural/Operational	assess processes	TMDL, NPDES, Guidance	separate drawdown effects from recovery	TX, UT	low - limited relevance	10, 16, 53, 60, 72, 105, 127
Climate Change Impacts	Climate change	assess future conditions	Research, recovery assessment	Effects of climate change on recovery	Europe, N. America	high – factor into recovery at decadal scale	1, 3, 57, 69, 86, 93
EPA lake health indicators (p. 61)	Indicators, Criteria and multiparameter	indicator	Guidance	trend, compare to reference	USA	low - general reference	115, 116, 132
Other criteria and indicators (p. 62)	Indicators, Criteria and multiparameter	criteria, indicator	Guidance	trend, compare to reference	W.USA	low - general reference	61, 62, 113, 114, 117
EU Water Framework Directive (p. 63)	Indicators, Criteria and multiparameter	indicator	Guidance	compare to reference	Europe	low - general reference	35, 36
Toolkit approach	Indicators, Criteria and multiparameter	holistic assessment	Guidance	various		medium - good approach for broad assessment	6, 50, 97

Appendix B. Glossary, acronyms, and abbreviations

Glossary

Advection: the movement of some material dissolved or suspended in the fluid.

Anoxic: water with little or no oxygen.

Anthropogenic: Human-caused.

CE-QUAL-W2: a water quality and hydrodynamic modeling framework in 2D (longitudinal-vertical) for rivers, estuaries, lakes, reservoirs and river basin systems, which models basic eutrophication processes such as temperature-nutrient-algae-dissolved oxygen-organic matter and sediment relationships.

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Cyanobacteria: a type of phytoplankton, sometimes termed "blue-green algae", that is nitrogen-fixing and toxic.

Diel: Of, or pertaining to, a 24-hour period.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Effluent: An outflowing of water from a natural body of water or from a man-made structure. For example, the treated outflow from a wastewater treatment plant.

Epilimnion: The shallow waters of a thermally stratified lake or reservoir that are relatively warm, well mixed, and interacting with the atmosphere.

Eutrophic: a fresh water body that has high nutrient levels, high algal biomass, and low clarity.

Gross Primary Productivity (GPP): the rate at which an ecosystem produces biomass by creating organic carbon through photosynthesis.

Hypolimnion: The deep waters of a thermally stratified lake or reservoir that are relative cool and isolated from the surface by density stratification.

Hypoxic: waters with oxygen levels reduced below saturation.

Littoral: part of a sea, lake or river that is close to the shore.

Mesotrophic: Fresh water bodies that have moderate nutrient levels, algal biomass, and clarity.

Metalimnion: In a thermally stratified lake or reservoir, the transition zone between the epilimnion and hypolimnion where temperatures are changing from well-mixed, warm, surface waters and isolated, cool, deep waters.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Oligotrophic: Fresh water bodies that have low nutrient levels, low algal biomass, and high clarity.

Oxidation: reaction with oxygen, or any chemical reaction that involves the loss of electrons.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Pelagic: located in the water column of ocean or lake waters, but not on or near the bottom.

Photic zone: the depths in a lake or reservoir were sunlight is sufficient for photosynthesis.

Percentile: A statistical number obtained from a distribution of a data set. For example, the 90th percentile is the value below which 90% of the data exists.

Periphyton: photosynthetic algae and other microorganisms that live attached to submerged surfaces in water bodies.

Phytoplankton: floating photosynthetic algae and other microorganisms that live in water bodies.

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural,

recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Reduction: a chemical reaction that involves the gaining of electrons by one of the atoms involved in the reaction.

Respiration (R): the process by which cells use oxygen to break down organic compounds and obtain energy.

Salmonid: Fish that belong to the family *Salmonidae*. Species of salmon, trout, or char.

Secchi depth: a measure of water clarity based on the depth at which the patterns on a Secchi disk can still be discerned.

Total Maximum Daily Load (TMDL): Water cleanup plan. A distribution of a substance in a waterbody designed to protect it from not meeting (exceeding) water quality standards. A TMDL is equal to the sum of all of the following: (1) individual wasteload allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a Margin of Safety to allow for uncertainty in the wasteload determination. A reserve for future growth is also generally provided.

Trophogenic zone: the depth in a lake or reservoir where primary production (photosynthesis) occurs.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

Acronyms and Abbreviations

AF	Anoxic Factor
AHM	Areal hypolimnetic mineralization
AHOD	Areal HOD
BOD	Biochemical oxygen demand
CBOD	Carbonaceous BOD
CVM	Cumulative volume method
DIC	Dissolved inorganic carbon
DO	Dissolved oxygen*
Ecology	Washington State Department of Ecology
ENSO	El Niño Southern Oscillation
EPA	U.S. Environmental Protection Agency
Fe	Iron (element)
GIS	Geographic Information System software
GPP	Gross primary productivity*
HF	Hypoxic Factor
HOD	Hypolimnetic oxygen depletion
Mn	Manganese (element)
N	Nitrogen (element)

NBOD	Nitrogenous BOD
NLA	National Lakes Assessment
P	Phosphorus (element)
R	Respiration
Si	Silicon (element)
SOD	Sediment oxygen demand
SRP	Soluble reactive phosphorus
TMDL	Total maximum daily load*
TP	Total phosphorus
TSI	Trophic state index
USGS	U.S. Geological Survey
VHOD	Volumetric HOD
W2	The CE-QUAL-W2 modeling platform*

(*see Glossary above)

Units of Measurement

°C	degrees centigrade
d	day
k	reaeration gas exchange rate
mg/L	milligrams per liter (parts per million)